Modelling the effect of technology on elite sport

Leon Ian Foster

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I. Abstract

Sporting equipment, and its associated set of rules, is used to facilitate athletic competition. As a result, sports technologies inevitably influence sporting performance. The level of this influence is dependent on the mode of technology used, as well as the type of sport in question. This study aims to model sporting performance, gauging the extent to which particular improvements can be attributed to technology. This information should assist in rule-setting by governing bodies regarding the use of technology in their respective sports.

Yearly top-25 performances were collected for men's and women's sporting events from 1891. These were validated using a number of different sources. Historic trends of the mean performance were plotted, revealing that there have been many anomalous rises and falls in performance, set against an underlying improvement trend. The periods of World Wars I and II are associated with a fall in performance. To avoid the data being skewed, performances from the period 1948 to 2010 were chosen to be examined in this study. A performance improvement index (PII) was found to be a useful tool with which to normalise changes in athletic performance across different sports, and to allow for comparisons. The PII was applied to running performances using 1948 as a baseline. An exponential function was then used to model the underlying improvement. This global improvement function was augmented with additional functions to account for the various interventions witnessed in each sport. In order to select functions to be applied, key dates of interventions were found from the literature. A manual stepwise fitting procedure was used to assess the appropriateness of selected functions, and a final model specified for each event. This method was applied to 38 different men's and women's events, in four separate sporting disciplines; running, field, freestyle swimming and speed skating.

Technology was found to be one of many interventions influencing performance; others included the increasing participation of different global populations within international sport, and the impact of the Olympic Games. It was found that from 1948 the maximum performance improvement ranged from 11.0% in the men's long jump, to 138.4% in the women's 3,000 m speed skating. The median improvement across all sports examined was 46.2%. These improvements can be attributed to underlying factors, such as developments in training techniques and globalisation. The greatest effect of technology was seen in long course speed skating, which showed an average technological influence of 30.0 % (mostly due to the introduction of clap-skates). Running demonstrated a negative influence from technology, with an average effect of -1.1 % (due to the introduction of fully automated timing). Overall women's performance has been found to display a greater influence from technology than men's. Performance-enhancing drugs were found to improve performance, but the impact of these appears to have declined in recent years.

In conclusion, technology has played a major role in the development of athletic performance, but has not been the dominant factor. Historically, gains in performance due to technology can be seen to have had a lesser impact on performance, with gains obscured by the natural development of the sport. However, any technological changes occurring towards the end of the natural evolution of sport are likely become more prominent, and their effects more significant. This means that in order to keep sports fair, the regulation of technology in sport should become more relevant than ever before.

Keywords: Technology influence in sport, Models of human athletic performance, trends in athletic performance, intervention modelling.

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VI. Nomenclature

Abbreviations

Adj.R^2	Adjusted regression coefficient
FAT	Fully automatic timing
FINA	Fédération Internationale de Natation
IAAF	International association of athletics federations
IOC	International Olympic committee
PII	Performance improvement index
R^2	Regression coefficient
SSE	Sum of squared error
WADA	World anti-doping agency
WWI	World War One
WWII	World War Two

Letters

t	Current performance figure	[s]
t_0	Reference performance figure	[s]
v	Velocity	[ms^{-1}]
F	Force	[N]
A	Frontal area	[m^2]
m	Mass	[kg]
a	Acceleration	[ms^{-2}]
P	Performance improvement from baseline	[%]
PII	Performance improvement index	[%]

Greek letters

ρ	Air density	[$kg.m^{-3}$]

Chapter 1: Introduction

1.1 Motivation for the research

Technology is the knowledge and application of tools, techniques, crafts, systems or methods of organization to solve a problem. Throughout history the use of many forms of technology has aided and influenced the entire human race, enabling us to build the modern world. Sports technology is any technology that has the possibility of influencing sporting performance and can be broken down into two categories:

1. **Those with a direct influence:**
   - Physical technologies are those aimed at reducing losses in power by reducing frictional forces between an athlete and the air, water or ice.
   - Improvements in the comfort and ergonomics during participation in sport
   - Non-physical technologies include improvements in training methods or developments in athletic skills which has the result of increasing power production.
2. **Those with an indirect influence:**
   - Changes in rules
   - Developments in procedures to enforce rules, e.g. timing systems, drug tests
   - Assistance with officiating decisions or changes in umpiring techniques.

Even though sports technology encompasses all these areas, the term typically refers to the equipment or hardware that aids sporting performance. A large amount of scientific and anecdotal evidence exists to show that individual performance levels in sports are influenced by sports technology. The magnitude of this influence on sport as a whole is not fully understood, and can be hard to quantify. This is because of the many different ways in which sporting performance is measured, as well as the number of other factors that contribute to overall sporting performance. A key question is; whether the levels of influence from technology in different sports can be meaningfully quantified.

Quantification of the effect of technology on sport will be useful in a number of ways: (1) in comparing historic sporting performances before and after the introduction of technologies; (2) in assessing which technologies maximise an individual athlete's own performance; (3) in enabling governing bodies to create rules concerning the use of technology. The latter, will then enable sport to be 'fair' and keep the spectacle of competition between athletes, increasing participation and interest in that sport.

1.2 Aims and objectives

The aim of this research project is to empirically model sporting performance and determine the magnitude of improvements that can be attributed to technology. This aim will be reached by achieving the following objectives:

1. To review improvements in performance in Olympic and other sports;
2. To review the historical developments of technology in Olympic and other sports;
3. To create mathematical models of human athletic performance in different athletic sports;
4. To use the mathematical models to determine the effect of developments in sports technology on human performance over time.

1.3 Thesis report structure

Following this introductory section, a literature review is presented where the current level of knowledge on the topic area of technological influence in sport is reviewed. Included within the review is a summary of existing models and methods to gauge developments in human athletic performance. Following this, a description will be given in the following three chapters of some novel methods developed to examine and quantify the effect of technology on athletic performance. These chapters are (I) data collection, (II) modelling performance data and (III) practical application of models.

The following four chapters (chapters VI - IX) explain the application of the methods used to account for interventions and their levels of influence in a selection of athletic sports. Each chapter is defined by sport topic area. Running performance is the first sport to be examined in this way. It was hypothesized that running is a sport in which technological advances have a minimal impact on performance. Therefore gauging the factors that have affected running performance is a useful starting point as it may be assumed that these factors will also influence other sports. The remaining three topic areas are: athletic field events (chapter VII), freestyle swimming (chapter VIII) and speed skating (chapter IX). Within each chapter a discussion is made on the historical interventions which have occurred in each sport, intervention modelling techniques are applied and the magnitude of these interventions are discussed.

The thesis will end with a discussion, conclusion and summary chapter where the magnitudes of the intervention within all sports examined are discussed. Within this final chapter, future work and outcomes from this study will also be explored.

Chapter 2: Literature review

2.1 Introduction

The use of technology to enhance performance in athletic sports is not new. There are many examples within ancient Greek history of sporting contests influenced by the use of technologies such as performance-enhancing drugs, Halteres (weights for long jumping) and starting blocks (Minetti & Ardigó 2002). There is no mention in ancient history of how much these technologies actually enhanced performance and is likely to be because there was not a universal way of quantifying sporting achievements. The pure competitive nature of ancient athletic competitions meant that sporting achievements were determined by which athlete threw the furthest or finished first.

The quantification of sporting achievement is a relatively modern invention, facilitated by development of timing and distance-measurement technologies in conjunction with databases of stored athletic performance. For this reason it appears there are only a few examples where the influence of technology in sport has been studied and quantified. One of the most well-publicized of these was the recent biomechanics study carried out by the IAAF, in which the energy consumption required for sprint running using carbon fibre prosthesis was explored (IAAF 2008). Oscar Pistorius is a double leg amputee and uses J-shaped carbon fibre prosthetic limbs attached to his lower leg to allow him to run. The study sanctioned by the IAAF, was carried out to ascertain the fairness of Pistorius competing in the 2008 Olympic Games in Beijing. The study found that the returned energy from the prosthetic blade is close to three times higher than that returned by the human ankle joint in maximum sprinting. In addition, the overall energy that Pistorius uses to run at a constant speed was 25% less than that expended by able-bodied sprinters. With this information the IAAF did not initially allow Pistorius to compete in the 2008 Olympics with able-bodied athletes. This ruling was later overturned and Pistorius would have been allowed to compete, but ultimately did not qualify.

The following literature review will be broken down into three segments. Firstly, examples where the influence of technology in sport has already been quantified will be examined. Secondly, examples by which human athletic performance has been quantified will be explored with a view to objectively measure the influence of different interventions. Finally, methods for analysing the evolution of athletic performance over time will be examined with the aim of quantifying the effect of interventions and technological changes on the natural progression of sporting performance.

2.2 Quantifying the influence of technology on sport

2.2.(a) Track and field

The Olympic Games are a massive sporting competition for both winter and summer sports. Many of these sports contain technology in one form or another, which undoubtedly influences performance levels. Stefani (2008) in his study to quantify Olympic performance improvements briefly estimated the influence of technology in Olympic sports through a simple percentage ratio. He attempted to quantify the influence of the rowing ergometer, the fibreglass pole vault, the Fosbury flop technique and the Clap skate. A year later Haake (2009) developed a method of measuring the influence of technology in four summer Olympic sports (100 metres, Javelin, Pole Vault and Track cycling) through the use of a performance improvement index.

Performance improvement indices (PIIs) have been proposed for the first time by Haake as a means of comparing performance statistics and to gauge the extent of the influence of technology in these sports. The performance improvement index for a specific sport is defined as a comparison of the energy expended by two athletes in carrying out a sporting discipline. In the case of the pole vault the performance index is simply the ratio of two potential energies, leading to a ratio of heights for a constant athlete mass.

Haake (2009) compared the earliest world records to the current world records as the basis of the performance indices. The level of technological influence on each of these sports performance indices were then gauged by examining the result statistics or changes in the energy equations due to technology changes.

The 100 metres was assumed to have no technology influence but had a PII of 1.21. The 1 hour cycling record was found to have a PII of 2.74 of which 0.34 was attributed to technology. The 4km individual pursuit cycling event had a PII of 1.35 of which 0.11 was technology related. The pole vault had a PII of 1.86 with 0.19 down to technology. Finally the Javelin had a PII of 1.65.

A difficulty with using the PII as a performance measure is that the index is very much dependent on the initial comparison performance figure. This means that careful and consistent selection of the initial performance figures is required in order to gain accurate PIIs. Haake (2009) used only world record performance data in his calculation. This data only represents maximum human performances in certain years. More detailed performance statistics such as the top performance each year or the average of the top 25 performances each year could be used to increase the accuracy of the PIIs. Additionally, world records by definition can only ever increase and so a drop in performance would be missed.

In addition, the PIIs calculated for the different sports only take into account technology influences and do not quantify other factors that influence performance. For example, the effect of World War or population change was not considered. Also in the formation of the PII formulae some assumptions were made when predicting the levels of energy expended during participation in these sports. For example, the PII equation in sprint running, assumes that the only force acting upon the runner is the aerodynamic drag force. This may not be the case as additional internal frictional forces may also need to be considered.

It was concluded by Haake that technology played a minor role in influencing performance improvements in sprint running. However this may not be the case and there may be many technology factors that influence sprint performance that are not immediately apparent in world record statistics. For instance, changes to the track stiffness, timing methods, starting blocks and clothing changes. Another final factor that was not taken in to account by Haake was potential changes over time in frontal body area of sprinters. If sprinters have grown in stature over time, then their frontal area will also have increased in proportion to this. This means that the indices determined for sprint running could be underestimated.

The PII is an example where performance statistics have been used to gauge performance improvements. The fraction of the PII that can be attributed to technology has been explored but there are still some factors that may have not been taken into account. The PII is a useful tool for gauging improvements in sporting performance and a means of quantifying other influencing factors in sport.

2.2.(b) Modelling the evolution of the tennis racquets

Technology features very prominently in the game of tennis, with the game based primarily around one piece of technology, the tennis racquet. Since the inception of tennis in the 1870s, tennis racquets have gone through many design changes, in particular from the 1970s up until today. Haake et al. (2007) examined the effects of the changes in tennis racquet design on the serve speed using a simulation program called "Tennis GUT" (Dignall et al. 2004). Tennis GUT brought together various physical models into one program. The models included the flight of a spinning tennis ball (Goodwill et al. 2004) racquet and ball impact, and ball and court interactions (Goodwill et al. 2005).

An analysis of representative racquets from the 1870s, 1970s and 2007 was carried out. Using Tennis GUT (Dignall et al. 2004), results showed that serve speeds have increased by around 17.5% since the 1870s with quarter of the change in serve speeds coming between the 1970s and 2007.

The results gathered showed that the ball launch velocity was 55.3 ms^{-1} using a 1870s racquet, 62.6 ms^{-1} using a 1970s racquet and 65 ms^{-1} using a 2007 racquet. From this data it was found that the time available for a return reduced by about 15% between the 1870s and 2007. It was concluded that the primary reason for the improvements seen in serve speeds was tennis racquet design. It was shown that racquets have become lighter and stiffer and the balance point has moved progressively away from the tip of the racquet. In addition to this, the transverse moment of inertia of the racquets has decreased markedly since the 1870s.

The performance measure for changes in the tennis racquet design was taken to be the change in serve speed. For sports like tennis where there are no performance statistics to examine, computer models like the Tennis GUT program will be required to examine technological influence levels in these sports. Sports where this is the case include golf, hockey and football.

2.2.(c) Technology changes in track cycling

Track cycling revolves around on one major piece of complex technology, the bicycle. There are many components that make up the entire bicycle and any changes to these components will influence cycling performance. Lukes (2006) used an analytical model to look at the effects of aerodynamic redesigns of track bikes on performance in the 4 km individual pursuit. The basic equation of motion given by Lukes was,

$$ma = F_p - F_d - F_r \tag{1}$$

where m is the mass of the bike and rider, a is the acceleration, F_p is the propulsive force of the rider, F_d is the aerodynamic drag force and F_r is the rolling resistance. The model created expands on equation 1 and incorporates among other parameters the bike efficiency, total drag coefficient, cross sectional area, scrubbing resistance and rolling resistance. The changes in bicycle technology, rider's clothing and seating position all can be examined by changing these input parameters. The output or performance indicator from this model is the time taken to complete the 4 km individual time trial.

In conclusion the track cycling model presented by Lukes can be used to explore the performance influence of different historic track bicycle designs, changes in clothing and body position and finally helmet design on overall track cycling performance.

2.2.(d) Summary: The effect of technology on sport

There are very few examples within the literature in which the effect of technology upon sporting performance have been quantified (Stefani 2008, Haake et al. 2007, Haake 2009). Models of sporting events such as Lukes (2006) track cycling model and Tennis GUT (Dignall et al. 2004) are examples of analytical models which could be used to explore the influence of different factors including technology in track cycling and tennis respectively. Haake (2009) attempted to universally gauge the effect of technology in sport though the use of a performance improvement index. Athletic performance was broken down to basic energy requirements and compared performances on this basis. Other methods in which athletic performances could be universally quantified will now be explored.

2.3 Quantifying human performance

Models that describe athletic performance could be used to quantify the effect of technology in a range of different sports. It appears that running is a well-studied athletic event and as such there are a lot of analytical models in existence which describe running performance. These are the first models to be examined.

Mathematic models of running emerged at the start of the 20th century and have been used to predict finishing times of different running events. Almost all running models use parameters attained from real life running performance statistics. This then enables the different models to accurately predict running performances from a set of input parameters. Some of these models have been used to predict the influence of altitude or wind on running performance. However there is no published literature regarding the influence of technology or human physiology changes on running performance.

The running models examined can be divided into four separate categories (1) models based purely on result statistics, (2) models based on Newton's second law of motion, (3) models based on energy considerations, and finally (4) a combination of these methods used in hydraulic modelling.

2.3.(a) Pure Empirical models

Empirical models of running performance are based solely around result statistics. Thus the accuracy of these models is connected to the amount and type of results statistics available when these models were created. Empirical studies of running began in earnest at the start of the 20th century, using newly collated records at events like the Modern Olympic Games. Kennelly (1906) was the first to use men's world running records to explore the relationship between the average velocity and the time taken to complete a running race. He developed an approximate law of fatigue for male runners, and applied a relationship between average speed v that can be maintained over a time T and course length L. Kennelly presented the following relationship for world record running performances,

$$\log T = \frac{9}{8}\log L - 1.2307. \tag{2}$$

Following on from Kennelly, Meade (1916) examined athletic records and also established a relationship between pace and distance for running events up to 5 miles. Francis (1943) followed on from these previous studies and created graphs of speed against the logarithm of racing distance. The equation Francis gave for his relationship was,

$$(\log d - 1.5)\ (v - 3.2) = 6.08 \tag{3}$$

where d is the distance in metres and v is the speed in ms^{-1}. This curve satisfactorily fitted race records available at the time for distances between 400 meters and 19km. Lietzke (1954) also created similar logarithmic graphs of distance against time for various running records. He attempted to demonstrate that a simple mathematical relationship does exist for all running events, which previous studies could not. Lietzke presented the relationship,

$$v = a^{1/k} d^{(k-1)/k} \tag{4}$$

for various forms of racing including swimming, where a is a constant, d is distance, v is velocity and k is another constant characterized by the type of racing records being examined. A constant of exhaustion, K' which equals $(k-1)/k$ was then calculated. For running events Lietzke calculated K' to be -0.239 for women and -0.009 for men. As with previous studies, Craig (1963) created logarithmic graphs of race distance against velocity for running records. As this was a later study, Craig had a wider range of performance statistics at his disposal. With this data his compared the world running records from 1920 and 1962, using the distance against velocity graphs and concluded that all running world records were improving.

2.3.(b) Newtonian approach

A runner's acceleration depends on the balance between propulsive force and resistive forces and a typical differential equation for explaining this is given by,

$$ma = F_P - F_R \tag{5}$$

where m is the mass of the runner, a is the acceleration, F_p is the propulsive force and F_R represents all the resistive forces. This equation is then solved and unknown parameters are estimated and validated with actual performances. Furusawa and Hill were the first to create models of running based on Newtonian equations (Furusawa et al. 1927a, Furusawa et al. 1927b). They found that there was an approximately linear relationship between propulsive ground force and running speed, and presented the following equation for calculating velocity, v at any time for a runner exerting maximal effort,

$$v = fga\left(1 - e^{-\frac{t}{a}}\right) \tag{6}$$

where f is a constant and related to build, strength, skill and fitness of runner (found to vary between 0.5 and 1.0), a is a constant that relates the air resistance to the mass of the runner and the velocity of the limbs, g is acceleration due to gravity, y is the horizontal distance covered, and t is the time.

Hill also explored aerodynamic drag and the effects of wind on sprinters. Hill (1928) estimated that a following wind of 10 miles per hour should improve the running times of a first class sprinter over 100 yards by about 0.3 seconds, whereas a head wind of the same magnitude would increase the time by about 0.5 seconds.

Nearly half a century later Keller used the basic ideas introduced by Hill and created another running model (Keller 1973). This model used similar force balance equations to predict running performance for different distances. The basis of the model is,

$$a = \frac{v}{\tau} = f(t) \tag{7}$$

where a is the acceleration, $f(t)$ is the total propulsive force per unit mass exerted by the runner, and τ is the damping coefficient (assumed a constant such that the resistance v/τ is a linear function of v). For sprint events where maximum force is exerted the equation can be written as;

$$v(t) = F\tau(1 - e^{-\frac{t}{\tau}}) \tag{8}$$

where F = f(t), the maximum force a runner can exert. The product $F\tau$ in equation 8 is the maximum velocity *v* of the runner, and the damping coefficient, τ is associated with the internal resistance forces of the runner.

Keller expanded upon Hill's earlier model and introduced parameters to represent the energy balances of the runner. Keller assumed that the runner had some initial reserves of energy, E_0 which are depleted according at the rate of working of the applied force *f(t)*. These losses are governed by the release of stored energy at a rate σ, and this is assumed to be constant. Keller related this constant σ to the maximum oxygen uptake of the runner. The equation of energy balance Keller proposed can be written as,

$$\frac{dE}{dt} = \sigma - fv \tag{9}$$

with the initial condition, $E(0) = E_0$. Finally, the available energy cannot be negative so, $E(t) \geq 0$.

Keller used optimization methods to calculate the optimum speed for different distances and showed that the solution had two parts. For races at distances less than a critical distance, D_c, the optimal strategy is for the runner to apply his maximum propulsive force throughout the race. However, for races longer than D_c this is implausible, as the runner would have no energy resources to go beyond the distance D_c. The runner must therefore control *F* with respect to time. For longer distance events the optimal strategy is to accelerate initially using the maximum propulsive force until a maintainable speed is reached. This maintainable speed is determined by assuming that the runner depletes all their energy stores when crossing the finishing line. D_c was found by Keller to be 291 m. This means that for running races of 400 m achieving a steady running pace is more beneficial than gaining a high maximal speed, and that the 400 m races is not an all-out sprint

Dapena and Feltner (1987) expanded on the force balance model created by Keller and used video analysis to predict the propulsive force exerted by runners. They also attempted to model fatigue and the change in this propulsive force over the course of a race. Statistical data was used to modify their model and adjustments were made to the aerodynamic drag term so that predictions matched real event data. Finally Quinn, (2003, 2004) modelled the 200 meters and 400 meters sprinting events using an extended Keller model. The new model included an air resistance term as well as a term to account for the athlete's reaction time to the starting gun.

2.3.(c) Energy approach

Energy models are based on the first law of thermodynamics; the chemical energy released, *C,* is equal to the sum of the useful work done by the centre of mass of a runner, *W,* plus the mechanical energy degraded into thermal energy *H,* represented by,

$$C = H + W. \tag{10}$$

Differentiating equation 10 with respect to time gives,

$$\frac{dC}{dt} = \frac{dH}{dt} + \frac{dW}{dt}. \tag{11}$$

As with the Newtonian models, this differential equation is solved and constants in the equation are tailored to form a close fit to actual performances. In some respects, these models are a form of sophisticated curve fitting. Ward-Smith (1985a) was the first to create a running model based on thermodynamic energy requirements in this way. The running model Ward-Smith created expanded on initial work carried out by Lloyd (1966, 1967) and was based on energy equations 10 and 11. Ward-Smith's model accurately modelled sprinting, middle distance and long distance events. Later Ward-Smith (1985b) extended the initial model to incorporate a deceleration phase in sprinting, which many other models based on Newton's laws of motion could not reproduce accurately.

Péronnet & Thibault (1989) commented on the limitations of Ward-Smith's model in predicting running performances in events of 10,000 metres and greater, and attributed this to the original Ward-Smith's model not accounting for the progressive reduction in aerobic power output as running distances increased. Péronnet & Thibault (1989) expanded on Ward-Smith's energy model and accounted for the progressive reduction in the aerobic power output by the inclusion of empirical correction factors. The model incorporated parameters such as A, the capacity of anaerobic metabolism, MAP, the maximal aerobic power and E the reduction in peak aerobic power with the natural logarithm of race duration.

Ingen Schenau et al. (1991) used data obtained from supra-maximal cycle ergometer tests to model the kinetics of the anaerobic and aerobic pathways of highly trained athletes. This data was then used to create a power equation which was incorporated into a model of running. This model appears to predict realistic times for sprints events even though it did not use performance statistics to obtain any parameters in the model. Following on from this, Pritchard (1993) used momentum and energy balance equations in the same way as Keller (1973). In this model an attempt was made to separately model the anaerobic and aerobic pathways for energy conversion. However no reference was made to earlier work done by Ward-Smith(1985b) and Ingen Schenau et al. (1991).

Linthorne (1994) undertook a detailed statistical analysis of track performances over a ten year period and found that on average male athletes benefited by 0.1 s from a $2ms^{-1}$ following wind. Based on this statistical analysis Ward-Smith (1999) updated his running energy model. A slight modification was made to the parameter for calculating the degradation of mechanical energy, to take account of the role of external work. In addition to this, a slight modification was carried out on the drag term to reflect the change in mean body angle relative to the horizontal. The drag area (Frontal area x coefficient of drag) was changed to 0.36 m^2. It was found that at a given running speed, degradation of energy to thermal energy increases with wind assistance and decreases with a head wind. The explanation for this relates to the body lean angle (θ) which is determined by the force balance on the body. With a head wind, θ can be reduced as the body leans into the wind. This position means that the body is more suitably aligned to generate the required propulsive force. Conversely, with wind assistance, θ increases and the body is less able to generate the propulsive force required.

2.3.(d) Hydraulic modelling approach

Perhaps the most comprehensive running models to date are those which incorporate the whole body human energy processes during muscular exercise in conjunction with Newtonian laws of motion.

The first human energetic models were presented by Margaria (1976) who proposed a three component hydraulic model to explain all human metabolic energy processes during exercise. Three human biological energy processes were modelled; these were oxygen consumption, lactic acid formation (glycolysis) and phosphagen breakdown (alactic energy). Each of the three energy stores were represented by a hydraulic vessel, fluid flows between the vessels accounted for human energy processes and the total energy expenditure was indicated by the flow of fluid from the system. Fluid flows of the system are represented by various differential equations. Different parameters and assumptions associated with the differential equations lead to various configurations of the energetic hydraulic model. Initially Margaria envisaged sixteen forms of the hydraulic model. However Morton (1986) rejected twelve of these forms based on known physiological facts and presented a generalised hydraulic model "M-M (Margaria-Morton) model" based on Margaria's original.

Behncke (1993) took a generalised hydraulic model used by Margaria (1976) and Morton (1986) in conjunction with basic newtonian laws of motion to create a comprehensive running model which has the ability to model all forms of running events. Behncke suggested that such a model could be applied to other forms of athletic sports. Behncke (1997) used his previously created model and applied running world record data to ascertain model parameters. He discovered that parameters found using world record data agree well with those given in the literature and those obtained by other means

2.3.(e) Summary: Quantifying human athletic performance

There are many models and methods which have been derived in order to quantify the different elements in running performance and could be adapted to model all athletic performances. However the majority of these models are complex and contain many different equations, parameters, and assumptions. From this it is difficult to universally model all event disciplines. On possible method that could be applied to all athletic events could be through the use of the universal human energetic model based upon hydraulic modelling equations (Behncke 1993). The use of this universal energetic model would need to be in conjunction with other unique sporting models and could plausibly be used to gauge the influence of technology in sport.

All but the very complicated analytical models of running use performance statistics in one form or another to fit terms in model equations. The more complex models use performance statistics as a gauge of how accurate model parameters are and make comparisons between model parameters found by other means. Therefore the majority of running models are a sophisticated form curve fitting based around existing performance statistics. Thus investigating the evolution of human performance statistics could be used as a simpler way of gauging the change in athletic performance over time without the need for complex human energetic models. This would also allow various forms of technological interventions to be quantified. Literature relating to the modelling of human athletic performance over time will now be explored.

2.4 Human performance over time trend analysis

Observations of chronological trends in nature fall into two categories: (1) random fluctuations over time (stochastic data sets) such as weather temperature changes year by year; (2) average trends over time (systematic data sets) such as population changes over time. Human athletic improvements over time appear to conform to a systematic data set, and have been evaluated as such in the majority of existing literature. Studies into human athletic improvements over time are therefore based upon linear and nonlinear regression theory, and predictions of future or past performances are based upon corresponding models.

2.4.(a) Linear models

Linear models are the simplest models applied to athletic performance over time. Linear models in the form *performance* = *ax*+*b* only consist of two constants the gradient term *a* and an intercept *b*. Performance is calculated at various dates denoted by the parameter *x*. The major disadvantages of these types of model is that they only apply within certain date limits and have little physiological basis, i.e. there is no future performance limit.

Ryder et al. (1976) examined male running performance data from the preceding 50 years for distances from 100 yards to 30 kilometres. Average speed was plotted against historical time in years and gradients of the linear trends varied with distance: 0.6 m min^{-1} $year^{-1}$ for the 100 m to 0.9 m min^{-1} $year^{-1}$ for the marathon. Ryder concluded that although there must be a physiological limit to the speed a human can run, however this limit did not appear within their current data set. As no other functional forms were present in the data Ryder applied the simplest linear regression models. Whip & Ward (1992) and Tatem (2004) also applied linear models to performance over time statistics. Both of these studies compared men's and women's running performances, and predicted future performances. Whip & Ward (1992) believed that women marathon runners would run as fast as men in 1998, with performances converging at 2 hours 1 minute and 59 seconds. Tatem (2004) predicted that women would run as fast as men in the 100 m in the year 2156 with a convergent running time of 8.079 s. The improbable predictions made by these latter two studies, highlights the unrealistic nature of the linear performance models.

2.4.(b) Nonlinear models

Nonlinear models have also been widely used to model human athletic performance over time. The nonlinear models are more complex and contain at least one more parameter than the linear models, which allows for the nonlinear behaviour.

2.4.b.(i) Polynomial

Using a polynomial nonlinear model, Mognoni et al. (1982) compared male and female records for running, swimming and ice skating over various distances. Justification for the use of a polynomial model stemmed from the wide use and the ease of fitting this type of model. The polynomial model follows the form:

$$v = a_0 + a_1 T + a_2 T^2 + \ldots + a_n T^n \tag{12}$$

where *v* is the dependent variable, speed and the *T* is the independent variable, calendar years of every record improvement. With data up until 1981, Mognoni et al. found that a tendency towards an asymptotic speed was not yet a general phenomenon; but the rate of record growth was decreasing in some of the selected events.

It appears that this study is the first study to consider the introduction of fully automatic timing in the mid-1970s and all records of runners in which the timing was manual were increased by 0.24 seconds for 100 m and 200 m and by 0.14 for 400 m. These correction figures came from the official differentials given by The Association of Track and Field Statisticians in 1980.

The general problem with polynomial models is that they do not account for a tendency towards an asymptote, which means that they are inaccurate when extrapolated. The polynomial model is in a sense similar to the linear models where the predictions are only valid within certain date limits.

2.4.b.(ii) Exponential and logistic models

Within the existing literature, exponential regression models appear to be the most logical and practical way to analyse athletic performance over time. This is because they all feature asymptotic limits, which can directly relate to a human physiological performance limit. In addition to this the rate of change in the dependent variable (athletic performance) is related to the difference between it and the asymptotic limit (the characteristic of exponential decay curves). This is demonstrated by the ever decreasing improvement margins that new world records or sporting performance seem to show.

Deaken (1967) references an earlier obscure publication 'Future progress in the mile' (Lucy 1958) whereby an exponential model, $y = Ae^{-B(n-1)} + T$ was proposed to approximate y, the n[th] world record, where *A*, *B* and *T* are parameters of the exponential model (as $n \rightarrow \infty$, $y \rightarrow T$). This asymptotic regression model can be rewritten as:

$$y = L + a\,e^{bx} \tag{13}$$

where *y* is athletic performance, *x* is date in years, *L* is performance limit and *a*, *b* are constants relating to the data set. Deaken used this initial model to compare predictions of his new sigmoidal curve model of the form:

$$y = a - \frac{2b}{\pi} tan^{-1}(cx + k). \tag{14}$$

where *a*, *b*, *c* and *k* were constants to be found in a fitting procedure and *y* was a measure of the performance at a time (in years) *x*. Deakin did not have access to present day computing facilities and his curve fittings were done by eye leading to results which are hard to replicate.

Chatterjee & Chatterjee (1982) used the exponential regression model shown in equation 13 as the basis of a more in depth analysis of the gold medal winning times in the 100 m, 200 m, 400 m and 800 m for males at the Olympic Games from 1900 to 1976. They argued that a meaningful model should represent the physiological considerations, that there is a limit for sporting performance and that equation 13 is the simplest model which represents the data. After exploring different mathematical models, Morton (1983) believed that an exponential decay model shown in equation 13 was the most practical way of predicting running performances for this type of data. Morton also considered the use of Gomperz and logistic models but suggested that the exponential model is an adequate approximation past the point of inflection found in these more complex models.

Blest (1996) examined the various parametric regression models that were found in the existing literature as well as a few that he proposed himself. Performance data consisted of the world record at 18 Olympic Games in the male running events (100m, 200 m, 400 m, 800 m, 1500 m, 5000 m, 10,000 m and the marathon (assumed to be 42,195 m throughout this thesis). Blest considered the use of three different non-linear models: (1) antisymmetric exponential, (2) logistic sigmoid curve and (3) Gompertz. The use of a Gompertz function had an advantage over the standard symmetrical logistic curve as it allowed for the future asymptote to be approached with a reduced gradient in comparison to the lower valued asymptote. In contrast to the logistic function is symmetrical and both asymptotes are reached by the same gradient.

Nevill and Whyte (2005) took nonlinear regression modelling one step further and suggested that a (flattened S-shaped) logistical curve would be more representative of athletic performance over time data, with an upper asymptote for maximum running velocity or performance and a lower limit that could be representative of a limit that exists without human competition. A sigmoidal model accounts for the start phase and early adoption of athletic events where there is low participation, low competiveness and amateurism dominates. The rate of improvement keeps increasing as the competing population increases and sport becomes professional and truly globalised. At an inflection point the rate of improvement decreases and as an athletic event becomes saturated and improvements in athletic performances reduces, this shown by the ever decreasing improvement steps. Nevill & Whyte's proposed model is given by the equation,

$$\text{Speed}\ (\text{ms}^{-1}) = \frac{\min + (max - \min)\ e^{b\,(date-y)}}{1 + e^{b\,(date-y)}} \tag{15}$$

Where *min* and *max* are the minimum and maximum predicted asymptotic world-record running speeds, *b* describes the rate at which the world-record running speeds accelerated during the 20th century and *y* is the centred year that this acceleration was greatest. Inflection points or centred years were found to be around the middle of the 20th century.

Berthelot, et al. (2008) conducted a recent study using the exponential model shown in equation 13 to model human sporting performance in a number of different disciplines. Using piecewise regression Berthelot essentially split performance data (world records), into different periods and subsequently applied the exponential regression model to data within each period. There was no justification for doing this other than this gave the best regression correlation coefficient values. Denny (2008) took Nevill and Whyte's existing model and applied this to yearly performance figures that were gathered from a variety of different sources. Denny predicted new limits to human performance based upon this new data sets and concluded that humans have almost reached these limits, shown by the plateaus in some of his data sets. All regression models found within the literature have been summarised in Table 2.1, where performance P at time t is denoted by the various function types with additional parameters a, b, c and d.

Table 2.1: Summary of linear and nonlinear regression models

Year	Name	Model	Type
1976	Ryder et al.	$P = at + b$	Linear, straight line
1992	Whip & Ward		
2004	Tatem		
1982	Mognoni et al.	$P = a_0 + a_1 t + a_2 t^2 + \ldots + a_n t^n$	Polynomial
1958	Lucy	$P = a + b\, e^{ct}$	Exponential
1967	Deakin		
1982	Catterjee & Chatterjee		
1983	Morton		
1983	Schutz & McBryde		
2008	Berthelot, et al		
1996	Blest	$P = a - b\,(1 - e^{-c \cdot t})^d$	Extended exponential
		$P = a + b\left(e^{-c\cdot(t-d)}\right)$ For t ≥ d $P = a + b\left(2 - e^{-c\cdot(t-d)}\right)$ For t < d	Antisymmetric Exponential
		$P = a - b\,(1 - e^{-(c-d\cdot t)})^{-1}$	Logistic
		$P = a - b\ e^{(-e^{(c-d\cdot t)})}$	4-parameter Gompertz
		$P = a - b\ e^{(-e^{c\cdot(t-d)})}$	Reparameterization of Gompertz
1998	Grubb	$P = a - b\,(1 + e^{(c-d\cdot t)})^{-1}$	Logistic
2005	Nevill & Whyte	$P = \frac{a\, e^{b\cdot(t-c)}}{1 + e^{b\cdot(t-c)}}$	Logistic sigmoidal (flattened s shape)
2008	Denny		
2008	Kuper & Sterken	$P = a - b\ e^{(-e^{(c-d\cdot t)})}$	4-parameter Gompertz

2.4.(c) Using regression modelling to account for technology changes

It may be possible to account for interventions like technology using regression techniques to model human performance with time. Deviations from the trend line could be accounted for by additional model parameters.

Examining the existing models, it appears that the linear functions do not accurately represent the trends seen in athletic performance. Polynomial models contain multiple parameters and do not have a limit. They also only work within a specific time period.

Exponential and logistic models appear to be the most appropriate as they represent the diminishing improvements in performance as a limit is approached. However some of the exponential and logistic models are very complex with lots of different parameters. Some of these parameters may not be required for the purposes of this study and it would be beneficial to select a human performance model with the fewest parameters and best fit. For example, if human performance trends do not follow an s-shaped function, complex logistic sigmoidal or Gompertz models will not be required. Morton (1983) explained that when performance data is past the point of inflexion, the use of complex multi parameter models is not required and a simple exponential function will suffice.

Also it is important to note that using discontinuous world record performance data results in unstable parameter estimation, with estimations being sensitive to the number of year between the last records. One solution to this could be the use of a continuous data set or yearly data figures.

Finally, the quantity of data has increased with time and more athletic performances have taken place and been recorded. This will inevitably increase the accuracy and validity of any model applied to the data. Also increasing the size of the data set; for example, expanding a yearly data set to the mean of the top 25 will also increase accuracy of any model fit.

2.4.(d) Summary: Human performance over time

To summarise, regression models for human athletic performance over time found in existing literature, could be a means to gauge the influence of technology as well as other factors on athletic performance. To account for all these influencing factors some slight modifications maybe required to the models. For example, changes may comprise the inclusion of extra terms, the addition of further parameters and changes to existing constants. The piecewise or segmented regression proposed by Berthelot, et al. (2008), has potential to be used further to specifically model step changes attributed to the introduction of technology or other external influencing factors.

2.5 Comparing human performance

Haake (2009) provides a simple energy comparison for a variety of athletic performances through the creation of a performance improvement index. Although simplistic in nature it is a useful tool for comparing different athletic sports using the same measure. The only other example where the comparison of different athletic events has been carried out is in a study by Stefani (2008). Stefani used a similar method to Haake to produce a dimensionless measure of performance improvement. However the ratios that Stefani proposes are only simple ratios of percentage improvement in performance times or distances. Stefani used performance statistics from all the modern Olympic Games and measured the improvement between the Games, using the winning performance as his baseline measure. In all Olympic Games Stefani found the average percentage Olympic improvement was 0.70 % for running, 1.56 % for jumping, 1.54 % for swimming 1.25 % for rowing and 1.62 % for speed skating. He concluded that events with more technical challenges exhibited about twice the improvement of running.

As with Haake (2009) Stefani (2008) also explored the physical laws that govern the athletic movements in running, jumping, swimming and rowing events. He defined the power requirements of the various events through different models and equations. Unlike Haake (2009) Stefani did not apply his raw power equations in his comparative ratios and therefore his dimensionless measure of performance improvement between sports are based upon different performance measures (i.e. distances or time) which makes it difficult to compare performance improvements between them.

A dimensionless comparative index which gauges improvement in different sporting events could possibly be used to compare the variations in improvements in these different events. Additionally, the dimensionless index could be used to universally quantify the effect of technology in different sports as Haake (2009) demonstrated. The accuracy of index calculations are related to the quality and amount of performance result statistics and therefore to gain a meaningful representation of human performance improvements over time, a large performance data set is necessary.

2.6 Discussion

Studies quantifying the effect of technology in sport are rare and only three examples have been found within the literature (Stefani 2008, Haake et al. 2007, Haake 2009). These are only preliminary studies and do not give a full representation of all technologies and their influence in different sports. Stefani (2008) and Haake (2009) showed that dimensionless quantification of performance is useful in comparing improvements in different events and could be a means to quantify the general effect of technology on sport. All the studies that examined the influence of technology on sport used a limited set of performance statistics, and could be improved with the use of more comprehensive performance statistics.

Analytical models have been used to gauge running performance and parameters loosely related to human physiological constants such as oxygen uptake and anaerobic threshold. Changing parameters of these models enables accurate representation of human running performance; however most of these models are eventually another method of sophisticated curve fitting. The majority of these models are complex making use of many modelling parameters. This makes it difficult to universally apply a single model to all events.

There are many examples where human athletic performance over time has been modelled; the best of these models appear to contain exponential or logistic functions with a theoretical limit which can directly relate to a human physiological performance limit. The PII (Haake 2009) could be developed and used in conjunction with performance-time models to examine improvements in sport as well as the influence of different interventions such as technology.

2.7 Conclusion

There are many analytical models which could be used to model human athletic performance and the effect of technology on sport. The majority of these models are complex and contain large numbers of parameters which are loosely related to physiological constants. Therefore, all analytical models can be viewed as a sophisticated form of curve fitting which is also underlying in performance-time models. Performance-time models are relatively simple, contain few parameters and easily applied to a range of different sports and therefore appropriate for use in this study.

All performance models require sets of performance data to obtain model parameters and constants. The detail of this performance data directly influences the accuracy and relevance of these models. It appears that currently all performance models at best use world record data sets. These data sets are not sufficient or detailed enough to examine year on year performance trends or step changes due to interventions such as technology. In conclusion, improved performance statistics are required for use in this study and the requirements of this data are discussed in the following chapter.

There are many ways in which athletic performance is recorded, usually in the form of a race time or a distance jumped or thrown. Comparing performance within the same sport and events is relatively simple, but inter-sport comparisons are more challenging. To quantify the improvement in sport and the effect of interventions such as technology a method needs to be found to allow for meaningful comparisons. The PII (Haake 2009) is a method for dimensionless comparison of athletic performance which in theory could be used to compare interventions such as technology across all sports.

It is concluded that the use of performance-time models in conjunction with a dimensionless index such as the PII is currently the most appropriate method to account for the improvements seen in athletic performance. It appears that some modifications to the performance-time models may be required to account for step interventions such as the introduction of different technologies.

2.8 Revised aims and objectives

In light of the literature review the original objectives shown on page 2 have now been slightly altered to the following:

1. To review sources of athletic performance statistics, the level of detail available and collate all available statistics;
2. To review improvements in performance in Olympic and other sports through the use of dimensionless indices and performance-time models;
3. To review the historical developments of technology in Olympic and other sports;
4. To devise new mathematical techniques to analyse performance base around a dimensionless performance measure and performance-time models;
5. Top apply new techniques to find the magnitudes of the step changes and other effects noticed in the evolution of human athletic performance;

Chapter 3: Methods I - performance data

3.1 Introduction

In order to determine the influence of technology in athletic sports, the evolution of human athletic performance over time first needs to be considered. Human athletic performance could conceivably be quantified through the use of athletic results statistics. There are many different types of athletic result statistics and a detailed understanding of their properties, including their limitations, is required before human athletic trends can be analysed.

There are many influencing factors which may have influence human athletic development over time, the introduction of technology being just one of these. The aim of this chapter is, therefore, to examine available statistics that describes the evolution of athletic performance over time, explain trends found within this data and finally postulate on factors that may have influenced these trends.

The objectives of this chapter are the following:

1. To describe the different types of performance data available
2. To explain the sources of athletic performance data and their validity.
3. To explain which data set will be used for the purposes of this study
4. To explore the trends in human athletic performance
5. To hypothesise on the factors that have influenced trends in athletic performance

3.2 Athletic performance

The development of athletic performance has been and still could be directly related to the evolution of the human race. Ever since humans evolved to become a bipedal species, bipedal locomotion at high speeds for short periods, as well as at slower speeds for extended periods has been critical for human survival. The former aiding humans to escape predators while the latter helped humans hunt for prey.

The advent of the wheel and other technological advances has meant that the importance of athletic performance for human survival has diminished. Instead, athletic sports have now become a popular form of exercise for the masses and for the elite few, international competitions have led to fame and fortune.

Since antiquity, human beings have competed against one another for survival. With the emergence of modern societies, adult athletic competitions have also surfaced as a means for human beings to compete against each other once again. Athletic competitions are more than likely to have commenced before written history, with events similar to the Ancient Olympic Games held in Greece from 776 B.C. onwards.

The modern revival of the Olympic ideal started with "The Wenlock Olympian Society Annual Games" dating from 1850, the forerunner to the modern Olympic Games which commenced later in 1896 (Findling & Pelle 2004). Throughout the 20th century the introduction of these and similar competitions has led to an increase in global competition between athletes from all over the world. Alongside the development of modern international competitions has been the ever growing of pool of results statistic generated from these organised competitions.

3.2.(a) Records of human athletic performance

Comprehensive athletic performance data is only available from the start of modern international competitions. This is helped by technological advances in gauging these performances, such as the development of measurement technologies, the metric system, and devices like the hand held stop watch. This means athletic performance can only be gauged where quantifiable records exist. Ancient athletic performances in which tangible records do not exist cannot be accurately determined and therefore cannot be considered.

Accurate records of athletic performance have been recorded through the collection of statistics since the start of modern international athletic competition in the 19th century. These historic records of sporting performance are an excellent gauge of historic human athletic performance and can be considered as practical scientific data (Kennelly 1906 & Meade 1916). This is because athletic performance data such as world records are only sanctioned after meeting clear judging criteria which are impartial. Furthermore, the accuracy of the timing methods or distance measurements is relatively high, with state of the art technology being used to obtain the most precise readings. In other words, records have always been collected in a controlled scientific manner. Due to the competitive nature of sporting events and the long term training undertaken by athletes before competition, it is assumed that this leads to the best possible performance by all competitors, implying that sporting records, especially world records, are a good indicator of human performance levels. The following quote by A.V. Hill in 1924 alludes to the notion that sporting statistics can be used within a scientific study.

"Some of the most consistent physiology data available are contained, not in books on physiology… but in the world's records for running…"

(A.V. Hill 1924 Herter lectures, John Hopkins University)

This indicates that it is possible to use athletic performance data to determine the influence of interventions such as technology. In an ideal world, repeated observations of performances with and without an intervention's influence is desired for the perfect experimental design. However, this is not possible in practical terms and with this study it is assumed that the influence of interventions can be distinguished at the historical date of their introduction.

3.2.(b) Types of performance data

The performance statistics available in the 100 m men's event have been examined and represented in graphical form in Figure 3.1.

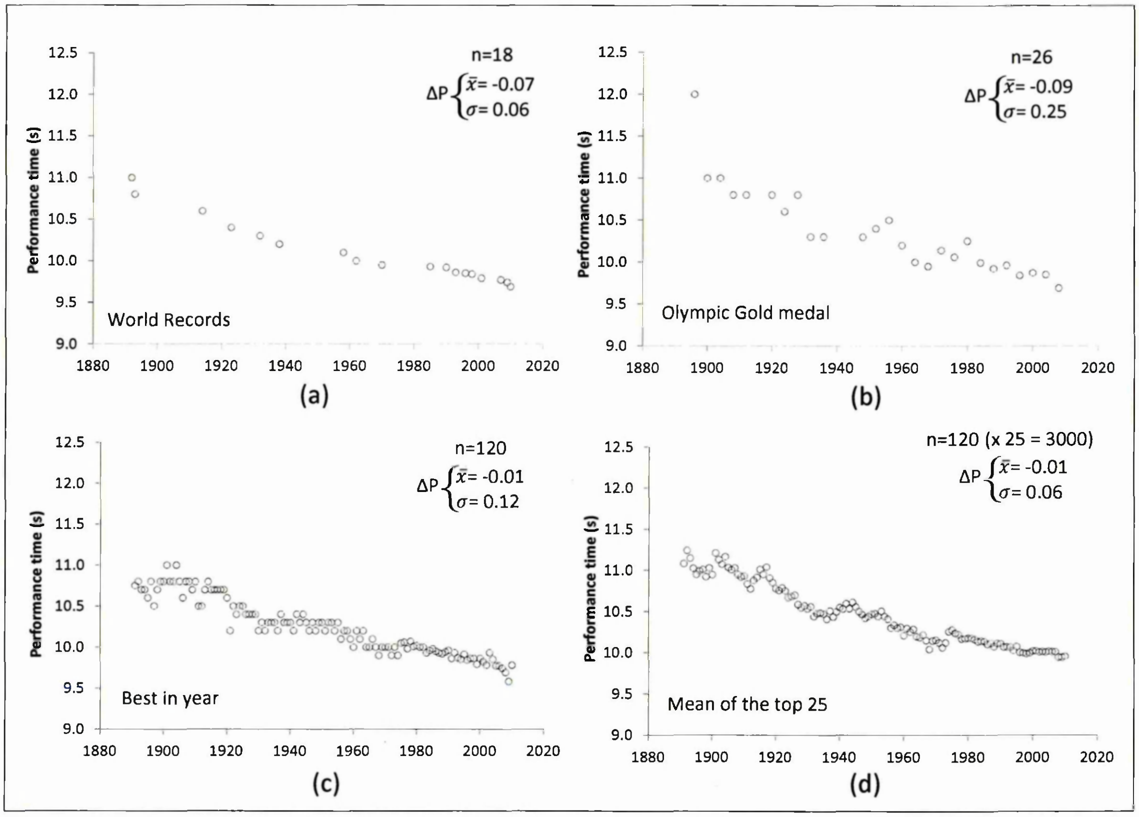


Figure 3.1: Performance time in seconds *P* against year of the men's 100 m running event shown in the form of (a) world records; (b) Olympic gold medal performance; (c) yearly best time; (d) mean of the top 25, shown with the number of data points *n*, the average of Δ*P* (change in performance) and standard deviation of Δ*P* (change in performance).

3.2.b.(i) World Records

The most basic level of recorded sporting performance can be found within the world record progression of each sport (Figure 3.1 a). World records are rarely set on a yearly basis and more commonly are separated by many years between each record. Since records began there have only been 18 world records set in the 100 m men's event. Another unique characteristic of world record data is that they generally never decrease; however, this is not true for all events as some are subject to outside interventions such as rule changes. One example of this is the men's and women's Javelin where rules changes to the javelin specification reduced world records. World records for most sports go back to the inauguration year of that particular event, meaning that world record data is generally available from the mid-19th century.

3.2.b.(ii) Olympic Games results

The next level of sporting result statistics that can be studied are the Olympic gold medal performances (Figure 3.1 b). This data set has a periodicity of four years and results for most events are available from 1896, the start of the modern Summer Olympic Games. The only Olympic performance years which are not available are 1916, 1940 and 1944. These games were cancelled due to the First and Second World Wars. Unlike world records, the Olympic data set has the advantage in that performance figures are periodic (every four years, with the exception of the war years) and do not necessarily show an improvement.

3.2.b.(iii) Top performance and top 25 performances

To increase the resolution of the historical performance data set, yearly top performance results statistics can be gathered (Figure 3.1 c) Arguably however the most comprehensive performance data sets available for this study are the yearly top twenty five individual performances (Figure 3.1 d). These data sets contain the best twenty five individual athlete's performances each year so that no one athlete is represented more than once in the list. This data therefore represents the elite field of athletes, and as such examining this data reveals what trends and factors have influenced the elite athletic community. To create a single yearly performance measure from the list of the top twenty five performances, a mean performance value can be used. This mean value is a good representation of performance levels of elite athletes, and is less influenced by extreme performances that can be found in world records or singular top performance data sets.

3.2.(c) Selection of a performance measure

The average drop between world record (ΔP) in the 100 m men's event was -0.07 seconds and the standard deviation was 0.06. The relatively low standard deviation shows that improvements in world records have been relatively consistent. However, using world records as a measure of historic athletic performance produces some major problems. Firstly, world records are not set on a year on year basis and there can be many years between world records. This makes it difficult to ascertain performance levels in a year when there was no world record set, and makes it impossible to gauge intervention at years with no world records. Additionally, world records only ever improve (bar rule changes), meaning world records will never show a situation when performance levels have dropped. Any intervention which reduces performance therefore cannot be measured. In the men's 100 m running event (Figure 3.1 a) there are only n=18 data points. The low numbers of data points also make it difficult to accurately model the data. For these reasons world records will not be used as a performance measure in this study.

The Olympic Games data set (Figure 3.1 b) has an advantage over the world records in that they have the ability to highlight an increase as well as a drop in performance. The Olympic data set also has an increased size (n=26) and consistent periodicity (4 years between data points) when compared to the world records, this makes fitting models more accurate. However it appears that there is large variability in this data set with the standard deviation of being relatively high (σ= 0.25) and the mean of ΔP at -0.09. Additionally, the Olympic data set does not encompass all years, so once again there is the problem when examining the effect of interventions in non-Olympic years.

The yearly top performance gives a periodic measure of athletic performance, places no constraints on the whether there is a positive or negative improvement and will be useful to gauge the effect of interventions as well the overall trend of athletic performance. However the variation in this data set it relatively high (σ= 0.12), and likely down to the extreme nature and variability of producing a top performance time. The most consistent and comprehensive data set and therefore the best for this study is believed to be the mean of the top 25. It is by far the largest data set, consisting of 3000 data points (25 yearly points) and has a low variability in ΔP (σ= 0.06). The lower variability of this data set enables interventions to be measured more accurately and generally increases the accuracy of the fitting of model functions. Finally if a trend is found to occur in this data set, it can be assumed that this trend influences the entirety of the elite field of athletes. As the main aim of this project is to explore the influence of technology upon elite athletic performance, the top 25 data sets were the preferred performance measure within this project.

3.2.(d) Sources of performance data

The rapid growth of the internet over the last twenty years has created a medium to store and distribute enormous amounts of sporting statistics quickly and easily. This has opened up a wealth of information to the common sports enthusiast as well to researchers. For the purposes of this study, performance data was collected from a number of different internet sources and where possible was cross-verified to ensure its validity. This was done by using a number of different historical texts, such as sport annuals or sport statistics books (Quercetani, 1964; IAAF 1972; Rabinovich, 2011).

3.2.d.(i) World records

In athletic events, world records for every sporting discipline are widely reported throughout the internet. There are a variety of sources that state world records but the only official sources of data are the governing bodies of each respective sport. For example the International Amateur Athletics Federation website has made available all track and field world records under the "Stats" section on their website (IAAF 2011). Similarly online records are available for swimming, (Fédération Internationale de Natation (FINA 2011)), and finally speed skating, International (Skating Union (ISU 2011)).

The progression of world records is not readily available on governing body websites, but rather contained within their records or libraries. Dedicated sport statisticians and researchers have collated these lists and created statistical websites devoted to the sharing of world record progression lists. Examples of these sites, include world record progression in running, swimming and speed skating events (Perkiömäki 2012; Sports records.co.uk 2012; Speed skating news 2012).

3.2.d.(ii) Olympic Gold medals

The Summer Olympic Games or the equivalent Winter Olympic Games are arguably the most widely reported sporting events, with detailed result statistics going back to the start of the Summer Olympic Games in 1896 and the Winter Olympics in 1924. With the advent of the internet, websites dedicated to the spreading of Olympic statistics have been created (DatabaseOlympics.com 2012). Additionally, the official governing body website (Olympic.org 2012) also holds records of Olympic performances. These websites enable the easy collection of Olympic statistics such as the gold, silver and bronze medal performances. Historical Olympic books are also a good source of performance data and can be used to cross verify website data (Rendell, 2004).

3.2.d.(iii) Yearly best performance and top 25 performances each year

The collection and verification of large amounts of historical performance data is required before accurate lists of yearly best performances or top 25 ranked performances can be assembled. Once again sport statisticians have devoted statistical websites to share this type of data. Michael Rabinovich has detailed database of track and field statistics and has comprehensive list of the top 25 ranked performances (Rabinovich 2011). For speed skating there is also a dedicated website which provides comprehensive top 25 ranked performances (Speed skating news 2012). It has been discovered that for swimming events, results statistics are less comprehensive, with the best source of data having top 25 ranked swimming performance going back to 1990 (SwimNews.com 2012).

Where data is not available on the internet, it has been found that researchers often hold records of yearly top ranking lists which were also collected for this study. For example Mathew Booth (Booth 2012) holds top 25 and top 10 performance data for certain track cycling events and also Nick J. Thierry (SwimNews.com 2012) holds top 3 ranked long course swimming performances going back to 1948. Direct correspondence with these statisticians was required to access and obtain permission to use the data for this study.

3.3 Data collection, formatting and validation

3.3.(a) Collection of data

Where performance data is available from statistical websites, performance figures were directly copied from the web page to a spread sheet. Lists were then created of all collected performance figures. Performance data were collected under two columns, the first containing the historical year of the performance and second containing the athletic performance figure.

Top 25 performances figures were collected in a different manner. In addition to performance figures, the typical format of a top performance list includes various other columns of information; such as athlete name, date of performance, location of performance suffix etcetera. A typical top performance list for 1891 in the men's 100 m sprint is shown in Table 3.1.The aim was to get a single performance figure for each yearly top ranking list. This was undertaken by extracting the top ranking performance figures for each year and transferring these data sets to a single spread-sheet (Figure 3.2). The mean of the top ranking figures could then be calculated. This then left two useable columns of data: year of performance and the performance figure, which in this example is the mean of top 25 performances.

Table 3.1: Top performance list in the 100 m men's running event in the year 1891.

			100 m - 1891			
Rank	Name	Nationality	Performance time (s)	Suffix	Location	Date of performance
1	Luther Cary	USA	10.75		Paris	Jul-04
2	Charlton Moneypenny	GBR	10.8	e+	Cambridge	Jul-22
2	G.W. Turk	GBR	10.8	e+	Chelmsford	Jul-18
4	Harry Jewett	USA	10.9	e+	Detroit	Sep-29
4	W.C. Skillinger	USA	10.9	e+	Detroit	Sep-29
6	Etienne de Ré	BEL	11		Brussels	
6	Mortimer Remington	USA	11	e		
6	B.C. Green	GBR	11	e+	London	May-11
6	David Basan	GBR	11	e+	London	Jun-13
6	Charles.L Bernard	FRA	11		Paris	May-21
6	A. Margis	FRA	11		Paris	May-21
6	J. Hébert	FRA	11		Valéry-en-Caux	Aug-30
6	Bellon	FRA	11		Neuilly s.S.	Sep-27
6	Peter Vredenburgh	USA	11	e+	Detroit	Sep-29
15	T. Barbarin	FRA	11.1		Paris	May-21
16	S. Edström	SWE	11.2			
16	E.K. House	GBR	11.2	e+	Stamford Bridge	May-23
16	A. Hamilton	CAN	11.2	e+	Woodstock	May-25
16	Andre Tournois	FRA	11.2		Paris	Jun
20	P. Calcoen	NED	11.25		Den Haag	Sep-06
21	J. Calman	GBR	11.3	e+	Bradford	Jul-18
21	A.S. Turk	GBR	11.3	e+	Westham	Oct-03
23	N.W. Biggs	GBR	11.4	e+	Cambridge	Mar-09
23	J.P. Shuter	GBR	11.4	e+	Stamford Bridge	May-23
23	P. Blot	FRA	11.4		Paris	Jun-21
23	G. Parsons	GBR	11.4	e+	Chelmsford	Jul-18
23	T. Tongue	GBR	11.4	e+	Eton	Aug-01
23	W. Seward	GBR	11.4	e+	Bristol	Aug-29
23	Abraham Proy	BOH	11.4		Budapest	Oct-18
	Alajos Szokolyi	HUN	11.4		Budapest	Oct-18

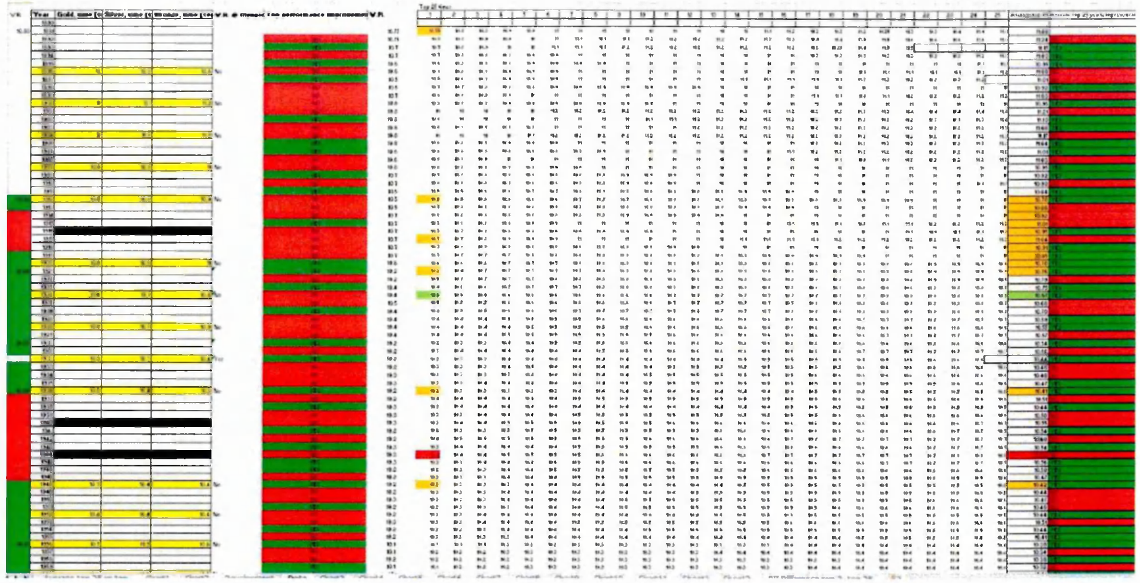


Figure 3.2: Spread-sheet showing the collated top performance figures and the calculation the mean of the top 25 for the men's 100 m sprint event

3.3.(b) Conversion of data

Performance figures in racing events were collected in various time formats depending on the length of the race. When examining performance improvements these figures were then converted to seconds and then to average completion speed of the race in ms^{-1}. Average speed was used as the preferred unit of performance measure as it is more representative of a tangible human characteristic. In contrast raw performance time is arguably an abstract concept invented to quantify sporting performances. The speed at which a human can run is also closely related to other physiological constants such as the rate of oxygen uptake. At certain running speeds oxygen uptake is linearly related to running speed (Pugh 1970). Representing multiple race event performances as average speeds within figures has the additional benefit in that axis scales are a lot more manageable, when compared to using raw performance times. Field event performance data do not need to be converted into a different performance measure, as all performance figures (distances/heights) are in metres.

3.3.(c) Validation of data

The data contained within yearly top performance lists such as that shown in Table 3.1 were checked for their validity by difference means. Firstly an initial data check was carried out. This was done by counting the number of data entries in the lists, checking the format of the performance measure, examining whether performances decreased throughout the lists and finally seeing whether there were any repetitions in data. The initial check revealed no errors or inconsistencies in all data sets, and it can be assumed that these kinds of checks were carried out during the compilation of performance lists.

Where possible the validity of quoted performance figures was checked and cross references were made against various other sources of data (Quercetani, 1964; Willoughby, 1970; IAAF 1972). It was inevitable that due to the large number of individual data entries in the performance lists, as well as the obscurity of data sources, that not all data could be cross-verified. All the data that could be checked were found to be accurate. Using an average performance figure each year also alleviates any individual errors or omissions in quoted performance figures. Due to the large number of data points, i.e. 25 in any one year, any error in performance figures, or missing data, will not significantly influence the average of the top performance figures. For example if the top time in the 100 m sprint event in 1891 (10.75) was omitted from the list, the mean of the top 25 will change from 11.08 to 11.11 (2dp), a change of 0.3 seconds or an increase of 0.23% (2dp). This error is typical of any omitted performance figure and considered acceptable.

3.4 Running performance data

As an exploratory study, running performance data was initially collected for a range of different men's and women's running events. It was hypothesized that technology has little influence on running and as such it is a good starting point to examine historical trends in athletic performance.

Lists of top 25 performances were collated for each event and a mean value obtained for each year. These values were then converted to average speed figures in ms^{-1}.

Shown in Figure 3.3 and Figure 3.4 is a summary of all collected performance data for men's and women's running events respectively. On first observation of the collated running performance data, it appears that all performances have improved since the start of each event. In addition to this it seems that the trends in performance improvements over time are similar across all running events. Furthermore, many of the performance trends seen in running appear to be reaching an asymptotic limit.

There also appears to be common features within the running data across both sexes and in different events. For example, two drops in performance are noticeable in the early and mid-part of the 20thcentury (1912-1920 and 1936-1948). This is likely to be attributed to the two World Wars which occurred within these time periods. These phases of performance decline have been highlighted on the following two figures.

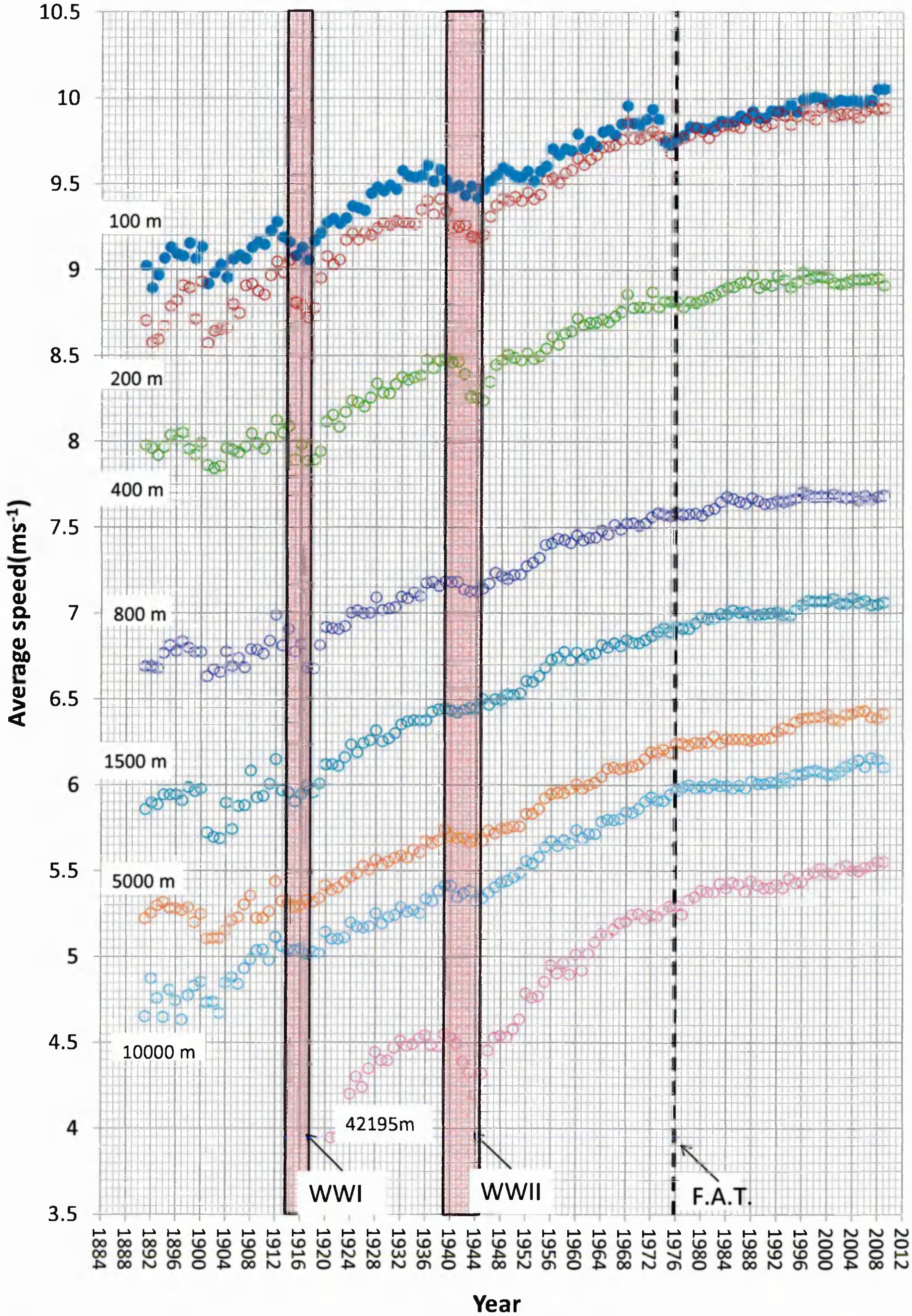


Figure 3.3: Men's running performance represented as average speed against historical year (mean of the top 25)

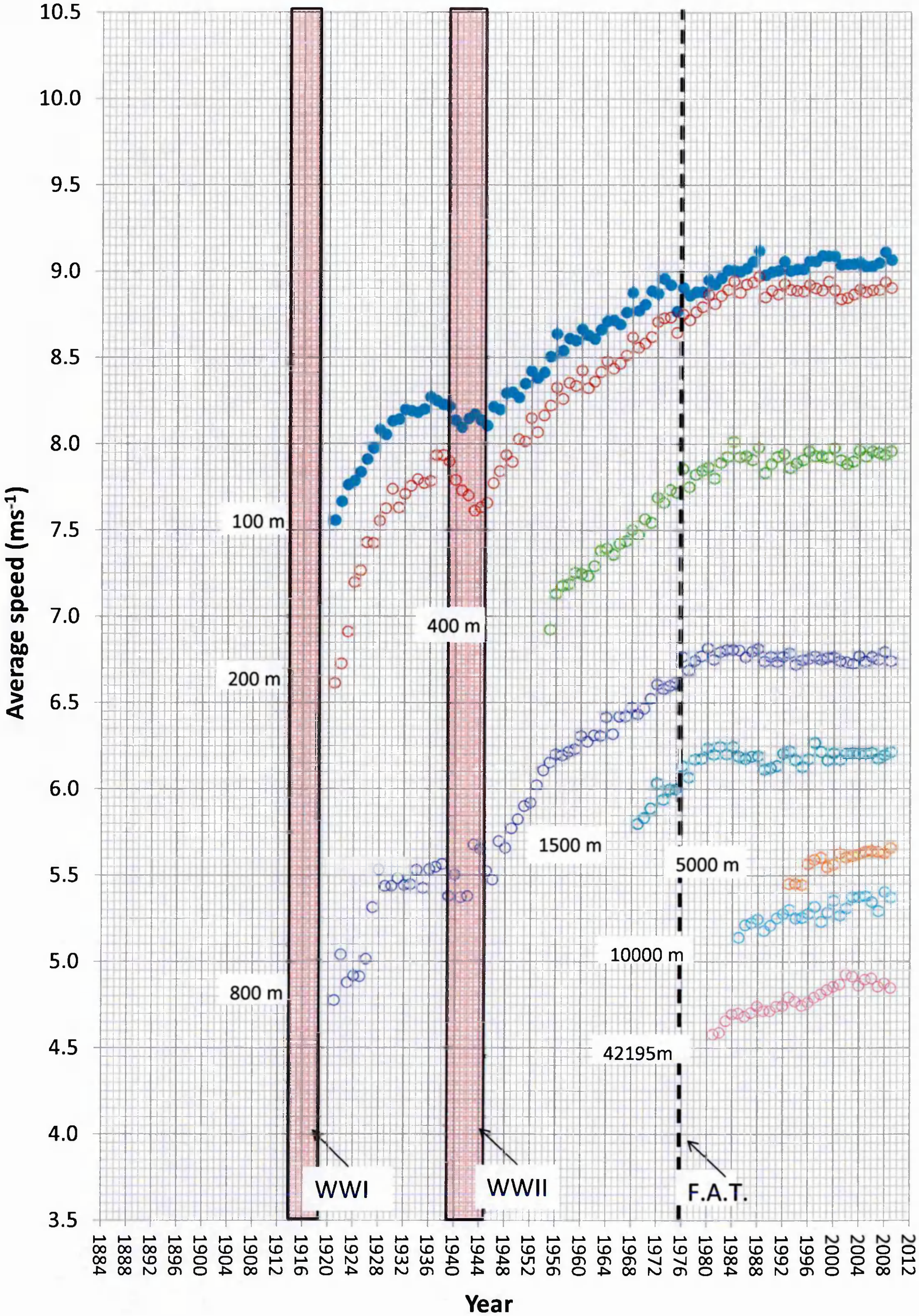


Figure 3.4: Women's running performance represented as average speed against historical year (mean of the top 25)

3.5 Influence of world wars

A small study was undertaken to examine the effect of the world wars on running performances. The percentage drop in performance time in different events was calculated for different historical periods. Table 3.2 shows five different historical periods over which running performance data were collected.

Table 3.2: Periods chosen to investigate the effect of World Wars

Period	Encompassing years	t_0	Period description:
1	1891-1912	1891	Pre-WWI, start of organised competitions
2	1912-1920	1912	WWI influenced period
3	1920-1936	1920	Interwar period
4	1936-1948	1936	WWII influenced period
5	1948-2010	1948	Post-war competitions up until present day

The average percentage change in performance time for the different running events were calculated for each historical period. This was carried out by using a reference performance time (t_0) at the start of the period, and the percentage change in performance time each year within that period based on this reference time. The average percentage change in men's and women's running events for these different historical periods is represented in Figure 3.5. (Note that in the standard 42,195 m men's marathon and women's, data is only available from 1921 onwards)

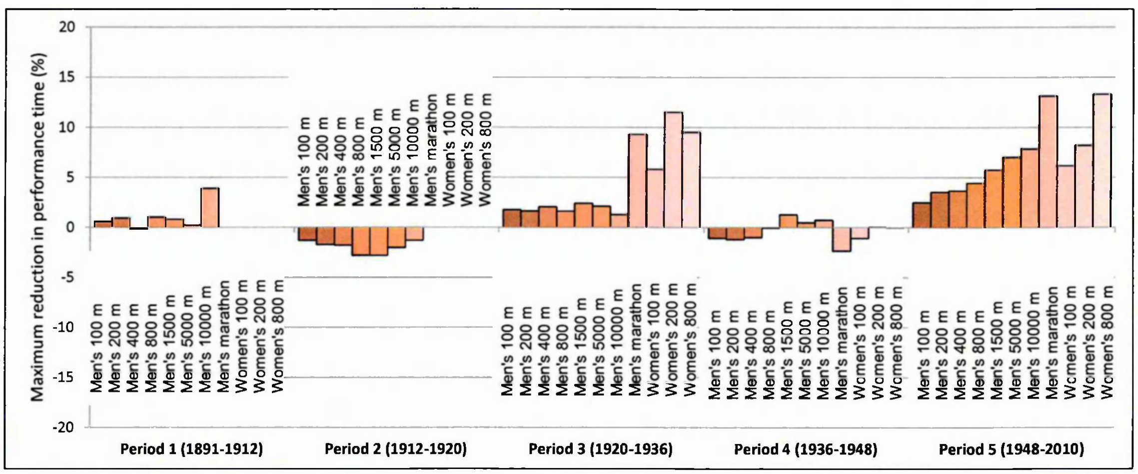


Figure 3.5: The average percentage improvement for running events for the different historic periods described in Table 3.2

Period 1 from 1891 to 1912 is the initial start of organised competition whereby on average there were small improvements seen in most running events. Figure 3.5 shows that within men's running events the greatest improvement was seen in the 10,000 m, with an average year on year drop in time of 3.89%. The men's 400 m showed no improvement and on average there was a drop of -0.15% per year in this event. The low average improvement values seen in period 1 could indicate either another unforeseen detrimental factor which has not been considered or alternatively could be attributed to the initial uptake of sport and slow developments in performance. The marathon, although started in 1896, was not run at a standardized distance until period 3 during the interwar years, and so was left out of the analysis for this period.

During the period influenced by WWI from 1912 to 1920 (period 2) all men's running events showed on average a drop in performance and we can conclude that WWI had a detrimental effect on running. On average the men's 1500 m event dropped 2.81 % each year, the most for his period and indicates this event was most detrimentally influenced by WWI. The least affected event during period 2 was the 100 m event with an average year on year 0.17% implying that men's 100 m was the least influenced running event during this period.

Period 3, the interwar period (1920-1936), saw the improvement of performances in all running events. The greatest year on year improvement was seen in the women's 800 m with an average increase of 11.51%. This is possibly because all women's events were relatively new and that the women's 200 m was at an initial stage improvement. It appears that newly introduced events experience a higher improvement 'gradient' in comparison to other events at the time.

During period 4, the WWII affect period (1936-1948), most running events appear to show little of no year on year improvement. This was especially true within sprinting events and on average the men's and women's 100 m deteriorated by 1.08% and 1.09% each year respectively. Also on average the men's marathon deteriorated by -2.36% per year. The 1,500 m middle distance event, and the shorter long distance events 5,000 m and 10,000 m showed an average improvement in period 4, but improvement levels were small in comparison to other periods.

Within period 4 the 1,500 m event showed the greatest year on year improvement, however this was still small in comparison to other periods. 1,500 m times improved on average by 2.96 % each year in the non-influence war periods, 1, 3 and 5 respectively. Whereas in period 4 there was only a 1.25 % increase in performance. One theory is that improvements in this event can be attributed to a rivalry between three Swedish runners, Arne Andersson, Gunder Hägg and Arne Ahlsén. This rivalry can be seen to have contributed to the world record being broken four times between 1936 and 1948. Sweden was a neutral country during WWII which allowed their athletes to continue competing and produce elite level performances. Additionally, there were a number of elite runners from Sweden and Denmark (also neutral) who also competed in the 5,000 m and 10,000 m distance events. Top 25 lists in this period in the 1,500, 5,000 and 10,000 m events were dominated by these runners and meant that they all showed some slight improvement. For other events like the 100 m and marathon, there were a minimal number of world class athletes from Sweden or other neutral countries. This meant that any athletes from these countries that continued to compete in these events could not improve existing records and this leads to negative or very small improvement values.

Within period 5 all the men's events saw large improvements in performance times, with the greatest improvement seen in the men's marathon with an average drop of 13.13% in time. Running events improved without the outside invention of World Wars in this period.

Table 3.3: Summary of the average percentage drop in performance during the two war influenced periods

Event	**Period 2 (1912-1920)**	**Period 4 (1936-1948)**
Men's 100m	-1.31	-1.08
Men's 200m	-1.73	-1.19
Men's 400m	-1.79	-1.01
Men's 800m	-2.79	-0.05
Men's 1500m	-2.81	1.25
Men's 5000m	-2.03	0.45
Men's 10000m	-1.30	0.72
Men's Marathon 42195 m	[redacted]	-2.36
Women's 100m	[redacted]	-1.09
Women's 200m	[redacted]	0.00
Women's 800m	[redacted]	-0.03

In conclusion, the war years detrimentally influenced all improvements in running performances. This effect of world wars has been quantified using a simple year on year percentage improvement calculation and results summarized in Table 3.3.

3.6 Selection of data set - 1948 onwards

World wars have been shown to be detrimental to the development of athletic performance. Any performance data that was obtained during the world war periods requires some measures to account for the detrimental effect. For the purposes of this study the effect of World Wars will not be modelled, but techniques derived in this study could be used to model this effect in future analyses. Therefore it was decided to use a condensed athletic performance data set that did not span world war influenced periods and did not require additional methods to account for the detrimental effects.

After the Second World War, the first Olympic Games to be held afterwards was in 1948, in London. This year marks the start of uninterrupted development of athletic performance and it was therefore decided to examine data from 1948 up until 2010, the latest year available at the time of this study.

Any comparison of performance requires a base line comparison year. For this purpose, 1948 was again a logical choice and within this study all performance improvements will be gauged from this baseline year.

In addition to this, any performance data available prior to WWII is less consistent across all sports; this is due to early technologies used to measure and record sporting performance, the reduced number of organised international competitions and as well as the lack of standardisation across all athletic sports and events.

The availability of performance data in a variety of athletic sports events from 1948 will now be explored. The available data will go some way to explain which athletic sports will be examined for the purposes of this study, as sports with an incomplete data set cannot be considered for analysis.

3.7 Available performance data from 1948 onwards

Table 3.4 summarises the performance data gathered for the purposes of this study. From 1948 there are extensive performance data sets for male and female track and field events (top 25 ranking lists). For the men's track and field events there is a complete data set; however in some women's events performance data does not go back as far as 1948. The availability of long course speed skating performance data sets are similar to that of track and field athletics, with a comprehensive data set from 1948 for both men's and women's events.

It was found that long course swimming had a reduced data set. Performance data going back to 1948 was only found for the freestyle, which is the most established swimming stroke. Additionally, only the top 3 performances each year were available from 1948.

After significant efforts, it became apparent that track cycling performance data was not as complete as first envisaged. Performance data in two events was found, but this data was only collected from the late 1960s and early 1970s onwards. There was also another problem in that indoor velodromes were not standardised until very recently, which means comparison of performance time figures would be difficult. Track cycling performances carried out on different velodromes of different lengths and corner specifications (banking angle and length) would be influenced by differing amounts depending on the velodrome. Some velodromes could improve performances and others could worsen performances. Correction factors could be a means to account for velodrome differences, but gauging these correction factors for each individual velodrome would be difficult without detailed architectural drawings of the tracks.. Therefore gauging the influence of external factors such as technology within the sport of track cycling could not be undertaken in full within this project.

Table 3.4: Summary of performance data available for the sports examined

Sport and event:	**Top 25 going back to 1948**		**Alternative data set from 1948**		**Data available - year from**	
Track:	Men	Women	Men	Women	Men	Women
100 m	✓	✓				
200 m	✓	✓				
400 m	✓	×				Top 25-1955
800 m	✓	✓				
1,500 m	✓	×				Top 25-1969
5,000 m	✓	×				Top 25-1983
10,000 m	✓	×				Top 25-1985
42,195 m (Marathon)	✓	×				Top 25 - 1981
Field Throwing:						
Shot	✓	✓				
Discus	✓	✓				
Hammer	✓	×				Top 25-1992
Javelin	✓	✓				
Field Jumping:						
Long Jump	✓	✓				
High Jump	✓	✓				
Pole Vault	✓	×				Top 25-1991
Swimming freestyle (Long course):						
50 m	×	×	×	×	Top 25 - 1990 / top 3 -1980	Top 25 - 1990 / top 3 - 1980
100 m	×	×	Top 3	Top 3	Top 25 - 1990	Top 25-1990
200 m	×	×	Top 3	×	Top 25 - 1990	Top 25-1990
400 m	×	×	Top 3	Top 3	Top 25 - 1990	Top 25-1990
1,500 m	×	×	Top 3	×	Top 25 - 1990	Top 25-1990
Speed skating (Long course):						
500 m	✓	✓				
1,000 m	✓	✓				
1,500 m	✓	✓				
3,000 m	✓	✓				
5,000 m	✓	×				
10,000 m	✓	×				
Track cycling:						
Individual time trial (1,000 m)					Top 10-1971 Top 25-1986	
Team pursuit (4,000 m)					Top 10-1966	

These sports were initially assessed for their appropriate level of technology influence (Table 3.5).

Table 3.5: The athletic sports and events examined within this study and the initial hypothesised technology influence within that sort

Sport	Event	Hypothesised technology influence
Running (track)	100 m, 200 m, 400 m, 800 m, 1500 m, 5000 , 10,000 m	Low
Running (road)	Marathon	Low
Field events: throwing	Shot	Low
	Discus	Low
	Javelin	High
Field events: Jumping	High jump	High
	Long jump	Low
	Pole Vault	High
Swimming (long course)	Freestyle 100 m	High
	Freestyle 200 m	High
	Freestyle 400 m	High
	Freestyle 1500 m	High
Speed skating (long course)	500 m, 1000 m, 1500 m, 3000 m, 5000 m and 10000 m	High

3.8 Factors that may influenced athletic performance

Potential factors contributing to athletic development are shown in Figure 3.6. Technology is believed to be just one of many influencing factors and before its effects can be measured, the other remaining factors need to be quantified in their own right. Not all factors will be relevant to all sports and each influence will be considered individually.

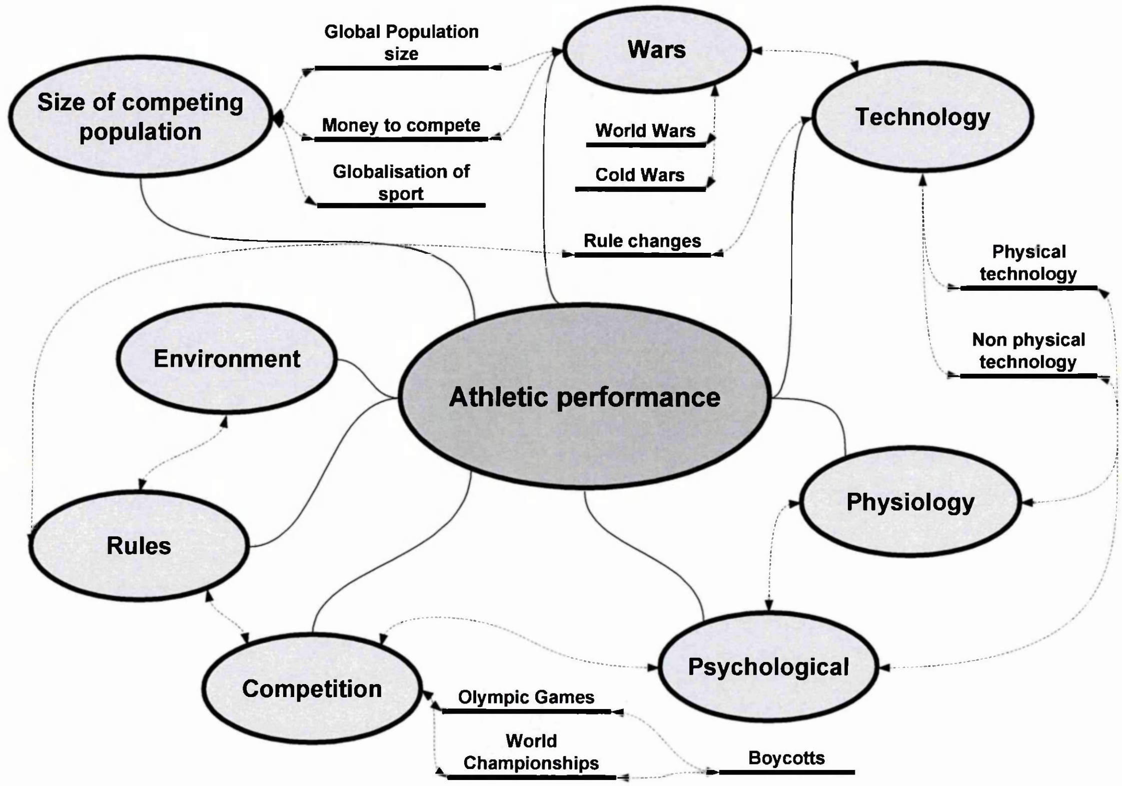


Figure 3.6: Possible influencing factors on athletic performance

3.8.(a) Environmental conditions

It would seem logical to assume that the environment within which an individual athletic performance takes place must inevitably influence the level of that performance. Some environments have characteristics that aid an athletic performance and others have a detrimental effect. The same environment for one event may be detrimental to performance, but this may not be the case for all events and some events may be influenced in a positive way. For example it has been found that the athletic sport of running in an environment with a reduced air density, like for that of athletic stadiums located at a high altitude, it is detrimental for marathon performances but enhances sprinting performances. This is because marathon or long distance running requires the use of predominantly aerobic metabolisms. At lower air densities the aerobic system of the human body cannot perform as well as at normal air densities, because there is a reduced oxygen level in the air. This does not influence the energy systems in sprinting performances as a sprinter predominantly use anaerobic (in the absence of oxygen) metabolisms. A sprinter actually benefits from a lower air density, as drag from air resistance is reduced. The higher speeds of sprint races compared to long distance races, means that drag reduction is most profound in sprint events and not tangible in the long distance event (Peronnet et al. 1991, Dapena & Feltner 1987, Lloyd 1967)

Wind is another environmental condition which can both be detrimental or beneficial to athletic performance. The direction and magnitude of wind can affect athletic events in different ways. A head wind (wind directed towards an athlete) can assist a discus thrower by increasing lift, but be detrimental to a runner as drag is increased. Specific models have been created to quantify the effects of wind on athletic performance. Davis (1980) and Dapena and Feltner (1987) have both created mathematic model in an attempt to model the influence of aerodynamic effects, including wind on running performances.

There are many additional environmental factors that could influence athletic performance including humidity levels, precipitation, temperature and noise. Some of these environmental factors influence the physical performance of the athlete (such as aerodynamics) while others the concentration and mental preparation of an athlete.

The influence of environmental conditions varies between different events and is hard to directly quantify. The use of the top 25 performance s in each year minimised the risk that any specific environment had a detrimental effect on the data.

This also applies to beneficial environmental factors, since governing bodies have specific rules which take these into account. For example, 100 and 200 m sprinting or long jump records are not valid if there is a tail wind of 2 ms^{-1}. There are also similar rules governing athletic performance made at altitudes of above 1000 metres. These performances are denoted with an "A" and are designated, altitude assisted performances.

3.8.(b) Rule changes/addition of new rules

Rules are set by governing bodies to make athletic competition as fair as possible. Without rules describing the athletic challenge, athletes may be tempted to undertake questionable tactics in order to win, which may not be in keeping with the Olympic ethos, and can potentially be unfair or even unsafe. An example of this is the use of performance-enhancing drugs in sport. Many substances are banned within the rules as they a deemed to be unsafe and not in line with the spirit of the Olympic ideal.

Rules may influence athletic performance. For example the false starting rules in sprinting events recently changed in 2010 so that all false starters are automatically disqualified from a race. This rule was specifically instigated to reduce the number of restarts and improve the spectacle. The original rule dictated that each athlete had one chance to false start before a second false start would lead to disqualification. This later changed so that only one false start was allowed, before any further false starts committed would result in instant disqualification for whichever athlete made the next false start. The altered rules concerning false starting may result in athletes being cautious at the start of the race, making sure they do not false start and reducing their reaction times, and subsequent performance time. Whether this is the case may be revealed with further performance data following the introduction of the new rule.

Other rules specify athletic techniques, for example that the javelin, must be thrown in a linear action, or that athletes performing the high-jump must take off on one foot.

Rule changes can have a major influence on performance; this is especially true when these rules relate to the use of technology. For example the specification of the javelin for both men's and women's events have been altered by the governing body of athletics the IAAF on the grounds of safety. A new specification for a javelin was devised to reduce the throw lengths, as throw distance had developed to a dangerous distance for other track athletes. Another example where governing body rules have influenced measured athletic performance is in swimming. In 2010 FINA banned the use of full polyurethane swim suits, a decision which has had a detrimental influence on swimming performances.

These major rule changes will need to be quantified to understand the evolution of athletic performance over time and quantify the influence of technology changes. Rules do not govern all technologies, and if a new technology is introduced existing rules may take some time to take new technologies into consideration.

3.8.(c) Technology introduction

Sports technologies fall into two categories; firstly the physical items of technology such as drugs and pieces of equipment used by athletes or adjudicators, and secondarily the non-physical knowledge such as athletic techniques or optimal nutritional and training awareness. Physical pieces of sports technology usually have a direct influence on athletic performance, whereas non-physical technologies usually have an indirect influence of athletic performance.

An example of a physical technology is the introduction of fully automatic timing (FAT) and the rule which made its use compulsory in 1976 for all major competitions. An apparent reduction in performance in sprinting performances can be seen for certain running events around the time the new rule was instigation. Within Figure 3.3 and Figure 3.4 there is an apparent instant drop in running performances for both men's and women's sprinting events (100 m, 200 m and 400 m) around 1976, this can be attributed to the introduction FAT. FAT is a form of race timing where a timing clock is automatically activated by a starting device, and the finish time is either automatically recorded, or timed by analysis of a photo finish. FAT systems use crystal oscillators such as Quartz to gain a higher level of accuracy over standard hand held devices. The typical accuracy of a FAT systems has been quoted at between 3 and 10ms, but can be up to 50 μs (Westenburg 1998).

The introduction of FAT has appeared to influence only the sprint races. This is likely due to the accuracy of pre-FAT hand-timing systems, which were accurate to only 0.1 s. It was not uncommon to have multiple athletes hold the world record in the 100 and 200 m before the introduction of FAT it has been found that original hand timing systematically under estimated performance times and there is a consensus that hand timed events should have correction factors applied of 0.24 s in the 100 and 200 m and 0.14 in the 400 m running events or hurdles. This is because of systematic human error in starting the hand help timing device. Studies have shown that the response time (reaction time + movement time) of a human to a single light stimulus is approximately 0.19 seconds. The difference between hand timing and FAT relates to the timing judge's response upon seeing the smoke from a starting gun and pressing the start button on a timing device (Galton, 1899, Welford 1980, Brebner and Welford 1980).

The main aim of this study is to quantify the influence of technology upon athletic performance and methods need to be devised so that the introduction of new physical technologies can be gauged. This will be discussed in the proceeding chapter.

Technology changes can also include the ever developing understanding of optimal nutritional programs or training routines. These non-physical technologies are somewhat intangible and their influence hard to meaningfully gauge. However these technologies universally influence all athletic sports and may not need to be quantified individually. Non-physical technologies like these directly influence general human as well as a top class athlete's physiology.

3.8.(d) Athlete physiology changes

There is plentiful evidence to suggest that the physiology of elite athletes has changed over time. It seems that sprinters have increased in height and mass, whereas marathon runners have decreased in mass. Norton and Olds (2001) proposed that the cause of an increase in sprinter size was due to an expansion of the reference population. This was through an increase in world population and widespread use of growth enhancing drugs. This is backed up by Rosenbaum (1988), who showed that the height and mass of the general population of Great Britain is increasing. Norton and Olds (2001) also suggested that the evolution of an athlete's physiology will continue to change in the future as sports become more specialised.

The changes seen in athlete physiology may also influence the aerodynamic characteristics of certain events such as running and some field events where the athlete's body shape influences performance e.g. long jump, pole vault and high jump (Dapena and Feltner (1987).

Changes in athlete physiology may be influenced by many different factors: an understanding of better training regimes, optimum nutritional knowledge and better food production techniques. It is therefore difficult to gauge the effect of individual factors which have influenced athlete physiology. For this project the influence of changes in athlete physiology will be treated as part of a global improvement trend, and not specifically quantified.

3.8.(e) World wars

Deterioration in performance is apparent in running during the period 1912 - 1920 and again from 1936 – 1948 (Figure 3.3 & Figure 3.4). These historical periods tie in with the two world wars, World War I from 1914 until 1918 and World War II from 1939 to 1945. During these war periods the countries heavily involved with the wars put all their resources and efforts into waging war and consequently sporting competitions were not seen as a high priority. The modern Olympic Games were cancelled three times since their inauguration in 1896 due to world wars: Berlin in 1916, Tokyo/Helsinki in 1940 and London 1944.

Conscription for the war effort is another possible influencing factor on the reduction in performance. During the First World War, the age of conscription for British soldiers was between 18 and 41, and by the end of the war this had been extended to between 17 and 51 (Parliament.uk 2009). Similarly in the Second World War conscripts were between the ages of 18 and 41 (History online 2009). Great Britain's conscription criteria were broadly typical of all countries involved in both world wars. The men expected to fight were at the prime age for peak physical performance and these groups inevitably included the typical ages of top athletes (Schulz and Curnow 1988). Reflecting the unprecedented devastation seen during these wars many millions lost their lives, and a high proportion of these deaths were seen in direct conflict, involving young male soldiers. In turn the athletic competing population or talent pool of potential male athletes was dramatically reduced. Estimates of fatalities in the First World War are around 16 million (Parliament.uk 2009) and for the Second World War, figures are around 50 million (White 2005). As a result, competitive sporting performance figures have fallen during these war time periods, because of the reduced numbers of competitors and official events where elite performance figures could be set.

3.8.(f) Cold War

The Cold War from 1945 to 1991 between the USSR and the USA may also have influenced athletic performance. This was not a conventional war, in contrast to the two world wars, and consisted primarily of heightened political tension and military stand-offs. One effect of the Cold War was a spirit of fierce national rivalry, specifically between the USSR and the USA, which extended to rivalries between the two nations at global sporting competitions. This can be seen as an influence on global athletic performances. George Orwell captured the essence of sport during the Cold War:

> *"Serious sport has nothing to do with fair play. It is bound up with hatred, jealousy, boastfulness, disregard of all rules and sadistic pleasure in witnessing violence: in other words it is war minus the shooting"*
>
> George Orwell 1945 (Tribune, The Sporting Spirit)

The well documented space race and nuclear arms races between the East and the West were accompanied by the lesser known race to produce top performing athletes who would win at all costs. The two countries which dominated sporting performance in the cold war time period were the USA and the USSR. This is not surprising as both these countries channelled vast resources into athletic sports. Much of these investments were hidden and secretive, such as the research in the field of performance-enhancing drugs. However there was also other evidence for this, such as the investments made in training villages, coaching and legitimate sports-science research. These steps to improve athletic performance have likely had a positive impact on performance levels, but whether all of these improvements were legitimate is a questionable issue (Wagg and Andrews 2007).

3.8.(g) Global championships: Olympic Games and World championships

The largest global athletics competitions are the Olympic Games followed closely by the Athletic World Championships. The Olympic Games have a periodicity of 4 years starting in 1896, whereas the Athletic World Championships commenced more recently in 1983 and since 1991 have had a periodicity of 2 years. Human athletes cannot perform at their peak for extended periods of time and it is clear that through periodic training regimes individual athletes plan peak performances during the Olympics and World Championships (Baker et al. 1995; Dick, 2002; Bompa & Carrera, 2005). This implies that during international competition years we are likely to see an increase in measured athletic performance with athletes performing at their peak at these competitions and with heightened competition at qualifying and warm up events throughout that year.

3.8.(h) Boycotts

There have been various boycotts of the Olympic Games since 1896, involving different countries and for a variety of reasons. Two significant boycotts of the Olympics Games were at Moscow in 1980 and Los Angeles in 1984, and related to the Cold War. Sixty-five nations boycotted the 1980 Moscow Olympics in protest of the USSR's invasion of Afghanistan. Most were Western countries, the highest profile of these being the USA. The following Olympics in 1984 were boycotted by fourteen Eastern Bloc countries lead by the USSR. The reason for the boycott was given on the grounds that the safety of their athletes could not be guaranteed, however it has been suggested that this was likely in response to the 1980 boycott (Wagg & Andrews 2007, Torres & Dyreson 2005). A boycott of the Olympics means that not all nations compete, resulting in a smaller competing population or talent pool. It might also mean that there will be less competition between athletes, which may lower the performances further still.

However the performance data set that was examined in this study was the yearly top twenty five and in theory athletes that did not take part in an Olympic Games due to boycotts could compete and set performance figures at different competitions throughout the same year. This means that there might not be an impact on overall top performance figures for that year.

3.8.(i) Globalisation and transport links

In the 21st century, the draw of large sporting events extends world-wide, whereas in the early 20th century only a few select nations and athletes had the opportunity to compete in the Olympics Games. This was because international travel was very time-consuming, expensive and difficult. At the turn of the century there were no commercial airlines, and athletes tended to have to voyage by sea. One early example of this was an international athletic meeting in 1894 between the universities of Yale and Oxford, held in Oxford. Typical voyage times across the Atlantic were approximately 2 weeks. Due to the early nature of amateur sport, only people with enough time and money had the opportunity to compete. In essence the fraction of the population participating with the opportunity to compete in athletic events was a much lower than it is today.

In our modern age the effects of globalisation, cheap air travel and the worldwide popularity of sport mean that the Olympic Games now draw on a large proportion of the worldwide population. This implies there is a significantly larger pool of athletes to draw upon and ultimately means that better performance athletes are more likely to be found within the expanded competing population.

3.8.(j) The size of the competing population

The greatest influencing factor on human athletic performance globally is believed to be the size of the competing population. Yang (1975) proposed that the larger the population from which a human is selected each year, the higher the probability that an exceptional athlete will be found by chance alone. Hence if the competing population size grows over time, athletic performance may also increase, leading onto the hypothesis, that global human population size is an influencing factor in human athletic performance.

The size of the competing population is directly related to size of the global population and other factors such as the level of opportunity to compete, available training venues, level of competitiveness of the event and also the popularity of the event. All these factors which influence the size of the competing population are very hard to gauge globally and for each individual country. However, if the fraction of competing population remains constant over time, then performances can be correlated to the global population size (Foster et al. 2010)

The study showed that the relationships found between athletic performance and global population size can be modelled using an exponential function similar to that used by Morton (1983).

The increase in global population size has been well documented, but the specific size of the competing population for all sports is not known. A method needs to be devised to model the influence of the size of the competing population upon athletic performance. The exponential model utilised by Foster et al. (2010) has demonstrated that it is possible to model the influence of global population size on athletic performance and a similar model could be once again used to model other influencing factors.

3.8.(k) Global factors

Global influencing factors are factors which universally affect all athletic sports and many of these have already been described. Factors mentioned include the development and adoption of non-physical technologies such as the use of better training techniques, optimal nutritional knowledge and physiological changes in athletes over time. Additionally, there could be more factors which are yet to be identified.

It is difficult to individually quantify the numerous factors which influence all sports, as their specific influence is hard to monitor or gauge. Therefore one solution to this problem is to account for all these global influencing factors in the same way. One global improvement function could possibly be used to model the influence of the entirety of global influencing factors. As all these global influencing factors occur in all athletic events, it is believed that their influence in different events will be similar if not the same. Therefore the same function can be used to describe all global improvement across all different athletic events.

As it has been found that an exponential function model can be successfully used to model the influence of global population size (Foster et al. 2010), the following chapter examines similar exponential functions, and comments on their validity for use as a measure of overall global improvement.

3.9 Chapter summary

In the absence of controlled scientific human performance measurements it is possible to gauge historic athletic performance through the collection of results statistic. These results statistics can be considered as accurate scientific data. Athletic sporting result statistics are available since the inception of modern international sporting events in the mid-19th century, with detailed top 25 ranked data available from the end of the 19th century onwards.

There are many types of sporting performance data available, these include; world records, Olympic performances, yearly top performances and yearly top ranking lists. However for the purposes of this study it has been decided to use the top twenty five ranked athlete's performances each year, as this gives the most detailed account available of performance trends within the in elite athletes.

An initial study revealed that running performance for men and women seems to follow the same universal trends which are likely to be seen in all athletic sports. It has been decided to use a single global function to describe the entirety of global factors which are hypothesised to influence all athletic sports.

There is a considerable body of evidence to suggest world wars have influenced sporting performance. This effect has been quantified by calculating the average year on year improvement in performance for different historic periods for running event. The effects of world wars need to be considered in any analysis that includes performance data from the relevant periods. Within this study it was decided to avoid using the war-years and consequently a reduced data set was chosen, starting from 1948. Choosing a reduced dataset also alleviated any uncertainties found in early data, and meant that there was a larger list of sports with a comprehensive data set to provide a good baseline value for performance improvement index calculations.

Hypotheses have been made about which interventions have influenced athletic performance. Every athletic sport is different, and each event will need to be examined on an individual basis to ascertain and gauge the different factors which influence athletic performance.

Chapter 4: Methods II - modelling performance data

4.1 Introduction

The comparison of performance across different sports is often difficult because of the different units of measurement used to describe them. Therefore it would be useful if a method could be found, which allowed for universal comparisons between all athletic sports. The performance improvement index (PII) devised by Haake (2009) may be one technique for doing this. Human performance has evidently evolved over time and various factors could contribute to this evolution: the increasing size of the competing population could be one of the main influencing factors. Modelling the influence of population on athletic performance has shown that a model that consists of an exponential function is very good at describing the trends seen within this type of data (Foster et al. 2010). There are many models with different functional forms that exist within the literature which describe the evolution of performance. These models are similar to that used to describe the influence of population size on athletic performance. However the best model which describes the evolution of top 25 ranking performance data is not yet known.

The aim of this chapter is to explain the methods used to universally gauge and model the evolution of human athletic performance as well as the techniques employed to gauge various factors which have influenced this evolution.

The objectives of this chapter can be broken down into the following:

1. To explore a method that allows for the comparison of athletic performance between different athletic disciplines.
2. To explain the model that best describes the evolution of human athletic performance and how it was chosen.
3. To describe and demonstrate three different methods for gauging the influence of technology in sport as well as other influencing factors such as technology.

4.2 Gauging performance improvements

4.2.(a) Percentage difference

A simple way to compare athletic performances is to find the difference between two performances from different historical periods. This is an easy way of comparing a single event of the same performance measure and magnitude, but this is not practical for comparing events of different disciplines. A more practical way of comparing performance figures could be through the use of percentage differences. (Stefani 2008) The percentage difference, *PD*, is calculated using the simple formula,

$$PD = 1 - \left(\frac{P_2}{P_1}\right).100 \tag{16}$$

where P_1 is the latest performance measure, and P_2 is a reference performance measure. The main disadvantage of this method is that different measures of performance cannot be directly compared, i.e. a percentage increase in height jumped cannot be compared to an increase in running speed.

4.2.(b) Performance improvement index

The PII, devised by Haake in 2009 is a means to compare various Olympic events. The performance improvement index breaks down the athletic performance in to the key energy requirements to undertake each sport.

4.2.b.(i) Running - aerodynamic index.

Haake (2009) proposed that in the case of running the 100 metres, the useful energy supplied by the athlete is mostly used to overcome the aerodynamic drag force F_d, and is calculated using the equation,

$$F_d = \frac{1}{2}\rho A C_d v^2 \tag{17}$$

where ρ is the air density in kgm^{-3}, A is the projected frontal area of the runner in m^2, C_d is the coefficient of drag and v is the velocity in ms^{-1}. Therefore the average power P required by the athlete to overcome the drag force for an average running velocity v_{avg} in ms^{-1} is now given by,

$$P = F_d v_{avg} = \frac{1}{2}\rho A C_d {v_{avg}}^3 \tag{18}$$

The total energy expended over distance s in metres and time t in seconds is now given by,

$$E = Pt = \frac{1}{2}\rho AC_d v^3 t = \frac{1}{2}\rho AC_d \frac{s^3}{t^2}. \tag{19}$$

The relative change in energy between two runs is given by,

$$PII = \frac{E}{E_0} = \frac{(AC_d)}{(AC_d)_0} \cdot \left(\frac{t_0}{t}\right)^2 = \frac{(AC_d)}{(AC_d)_0} \cdot \left(\frac{v}{v_0}\right)^2 \tag{20}$$

where t_0 is the reference performance time, t is the comparison performance time in seconds and E/E_0 is the ratio of energies required to undertake the running event. Assuming that there is no change in the frontal area A or the coefficient of drag C_d, the PII can be written as:

$$PII = \frac{E}{E_0} = \left(\frac{t_0}{t}\right)^2 \tag{21}$$

4.2.b.(ii) Field events - potential energy index

The performance improvement index developed for the pole vault event is based upon the amount of useful potential energy required to achieve a performance height. From this assumption the index for the pole vault is given as:

$$PII = \frac{E}{E_0} = \frac{(mgh)}{(mgh)_0} = \left(\frac{h}{h_0}\right) \tag{22}$$

where m is the mass of the athlete, g is acceleration due to gravity h_0 is the reference performance height and h is the comparison performance height. Assuming a fixed athlete mass, the index ratio cancels down to two comparable performance heights. This index is the same for the other vertical jumping events i.e. the high jump.

For throwing events and the long jump the performance measure is the distance thrown or jumped. Assuming that the trajectory of the throw or jump traces a perfect parabola, there are negligible aerodynamic effects and a launch angle of 45°, the height attained by the throw or jump is proportional to the distance gained. This means that the performance improvement index will be the ratio of distances and the equation is comparable to equation 22.

4.2.(c) Limitations of the PII

There could be some limitations of the performance improvement index. Firstly for the derivation of the aerodynamic squared ratio the main assumption is that the primary energy use in running is to overcome the drag force experience by the athlete. This may be true but there may be other energy requirements that are not considered. For example energy required to overcome the resistive forces of the muscles to produce motion of the body or the level of efficiency for different athletes. There is currently incomplete knowledge surrounding the exact force and energy requirements of a running or athlete performing an athletic motion.

In derivation of the aerodynamic index a runner is also assumed to be running at a constant speed, which means that the acceleration phase of a running race is not considered. This is not thought to be a problem as it has been found that the acceleration phases of different running events are very similar. Take for example the 100 m sprint event, the characteristics of the acceleration phase is similar for all athletes and therefore energy ratios as used in the performance index will not be affected. This is assumed to be the same for all running events.

Another assumption is that the frontal area of running athletes has historically remained constant. This is evidently not the case as it appears sprinters have got taller and heavier and long distance runners have remained around the same height but have reduced their mass. This change in mass and height has influenced the frontal area of runners and index calculations can be adjusted accordingly.

The potential energy index uses fewer assumptions for its derivation. The main assumption is that the mass of an athlete or throwing equipment is constant. This assumption holds true and can be controlled for the throwing equipment, but may vary for athletes competing in jumping events as with running athletes.

The performance improvement index is the first iteration to universally quantify athletic performance using baseline energy requirements. The assumptions made enable simple ratios to be created in order to quantify performance improvements and the size of interventions. For the purposes of this study the performance improvement index is therefore used as a comparison tool to gauge the size of interventions and make inter sport comparisons.

4.3 Selection of the functional form for global athletic improvement

Performance data was collected for men's and women's 100 m, 200 m and 800 m from 1948 to 2010 and converted in performance improvement indices, with the baseline performance set at 1948. These data sets are shown graphically in Figure 4.1.

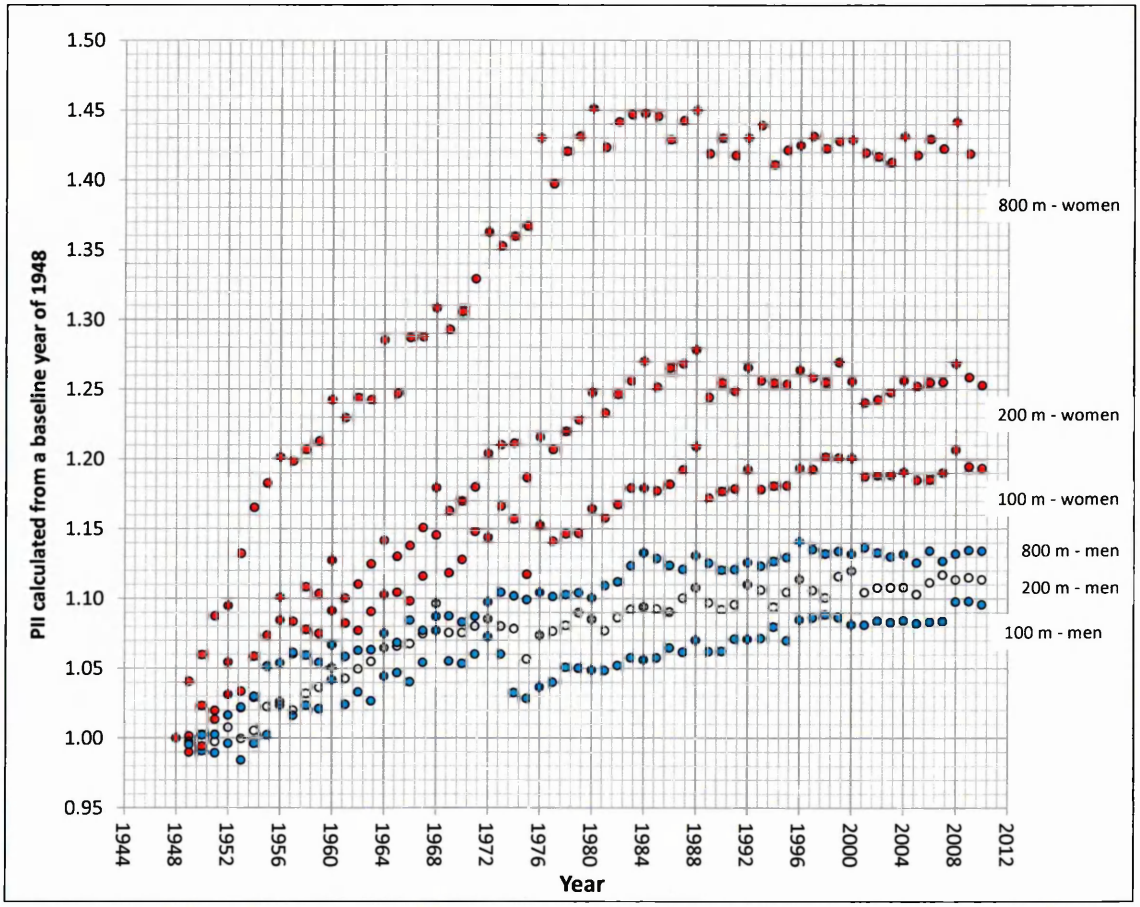


Figure 4.1: Running PII data set used to find the best fitting exponential function to be used for the global improvement function

A single functional form that best describe global human athletic development was selected based upon the improvements seen in running performances. Table 4.1 shows a summary of regression models and the goodness of fit values obtained from each of the functions when applied to the selection of six running events. These events were selected as they contained full data sets from 1948 and include both sexes.

The mean goodness of fit values: sum of squares error, regression coefficient and adjusted regression coefficient are the values gained from applying each of the models to the different running performance data sets. These values give an indication of the goodness of fit each model has to the various data sets examined. The shaded models in the table are the models with the best fit for the data sets (lowest SSE and highest R^2 adjusted).

Table 4.1: Summary of human athletic performance models and mean goodness of fit values when applied to mean of top 25 data (PII form) for men's & women's events (100, 200 and 800 m), best models highlighted

Model no.	Model function	Type and reference	Degrees of freedom	Mean sum of squares error	Mean r^2	Mean r^2 adjusted
1	$P = a + b \cdot e^{(c \cdot t)}$	Exponential (Morton 1983)	3	0.012	0.946	0.943
2	$P = a - e^{((-b) \cdot c^t)}$	Extended exponential (Ratkowsky 1983)	3	0.010	0.949	0.947
3	$P = a - d \cdot e^{((-b) \cdot c^t)}$	Extended exponential	4	0.010	0.944	0.940
4	$P = a - b \cdot e^{(-c + (d \cdot t))}$	Logistic (Blest 1996)	4	0.012	0.946	0.942
5	$P = a - b \cdot e^{(-e^{(c - (d \cdot t))})}$	Gompertz (Blest 1996)	4	0.011	0.947	0.943
6	$P = a - b \cdot e^{(c \cdot (t - d))}$	Reparameterization Gompertz (Blest 1996)	4	0.043	0.880	0.872
7	$P = \frac{a \cdot e^{(b \cdot (t - c))}}{1 + e^{(b \cdot (t - c))}}$	Logistic (Nevill & Whyte 2005)	4	0.011	0.947	0.944

The models consist of parameters *a*, *b*, *c* and *d* which describe the model shape; *P* is the performance improvement index and *t* is the historical year in centuries from 1800. *t* was changed to these units to keep the exponential parameters to a manageable size and these units for time are used in application of any model throughout this study. An Excel spread sheet was used to minimise of the sum of squared error (SSE) term using the solver function for all the models. The solver function uses a generalised reduced gradient algorithm which outputs model parameters for the lowest SSE (Walsh & Diamond 1995). Each model was then applied six times to the different data sets.

4.3.(a) Why not a sigmoidal model

As explored in the literature review section human athletic performance over time appears to takes the form of a sigmoidal "s shaped" function (Nevill 2005) with inflexion points occurring in the latter half of the 20th century. To simplify this study it is assumed that in 1948, improvement in human athletic performance is at a maximum, past the theoretical inflexion point and improvement diminishes as saturation of athletic events occurs. This means a more simple exponential decay function is only required to model the later section of the S shaped curve. Fewer model parameters are required for an exponential function, thus making the modelling processes simpler. The implications of using a three parameter exponential model are discussed in the final chapter.

4.3.(b) Criteria for model selection

Wellock et al. (2004) gave six different criteria points from which to select the best growth functional forms in biology. Assuming that improvements in human athletic performance follow similar growth patterns to that found within nature such as nuclear decay and local population growth, the same criteria can be used in selecting the best model function to describe human athletic improvement. The criteria for selection are as follows:

1. Fewer parameters are preferred
2. Functions in which the parameters can be given a theoretical meaning are preferred
3. Functions with the ability to be expressed in the "rate as a function of the state" are preferred
4. Biological growth should be seen as a continuous process
5. Functions with an asymptotic value are preferred
6. Functions that predict that relative growth rate will decrease continuously towards zero as time evolves are preferred.

All the functions described in Table 4.1 conform to the majority of the selection criteria, but not all parameters in all models can be given theoretical meaning (criterion no. 2). According to selection criterion no. 1, fewer parameters are preferred and the reasoning behind this is to keep a model as simple as possible and not use redundant additional parameters. The model examined in relation to modelling running performance improvement, with the best fit and the least number of parameters (Table 4.1) is the extended exponential (Ratkowsky 1983), model (no.2). This has been re-written as:

$$P = L - e^{-a \cdot b^t} \tag{23}$$

where *L* is the limit of the exponential function relating the theatrical limit of human athletic performance, *a* and *b* are the parameters of the exponential equation and *t* is the historic year in centuries from 1800 (i.e. at the year 1948, t = 1.48) . This model uses the fewest parameters for the highest adjusted regression coefficient and was used as the global improvement function to describe the underlying rise seen in all performances. Figure 4.2 shows the global improvement function fitted to the men's 100 m performance data from 1948.

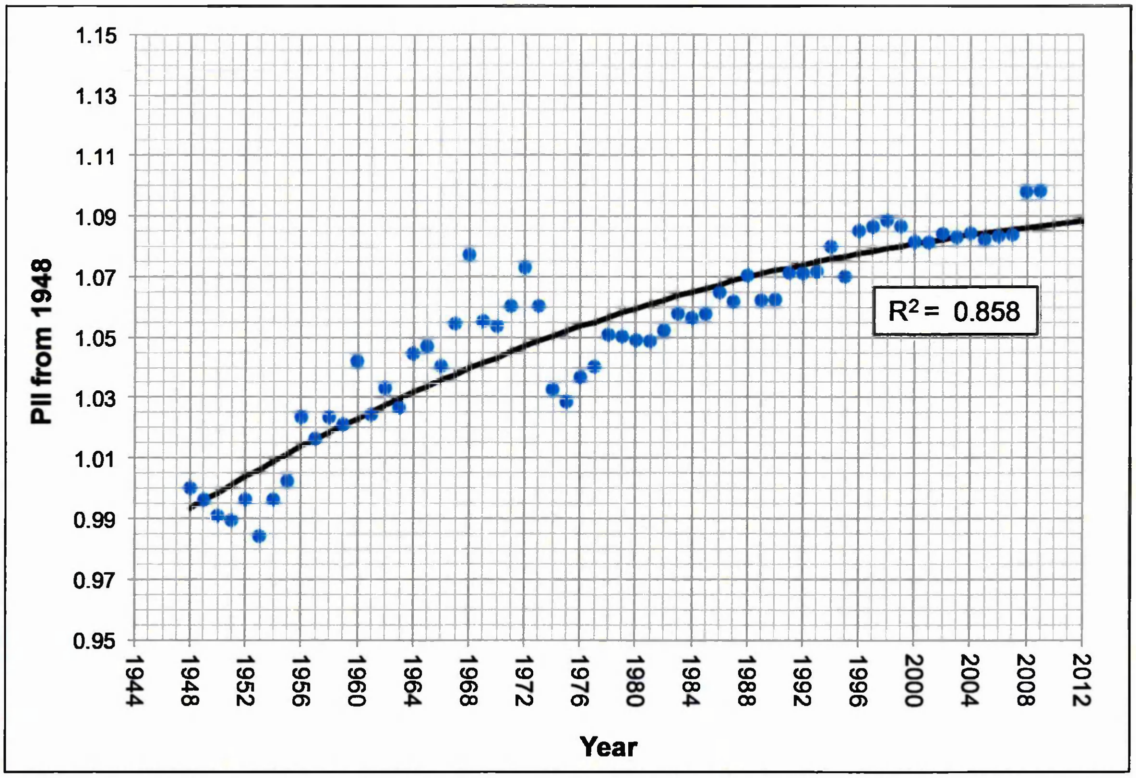


Figure 4.2: Performance improvement index change over time for the men's 100 m sprint with the addition of a global improvement model

4.4 Intervention modelling – levels of technology influence

Within the global improvement of athletic events there are often external intervention factors which also could influence athletic performance improvements such as the step change between 1973 and 1974 in Figure 4.2. These extra interventions do not necessarily occur across all sports and need to be analysed on a sport by sport basis. For the purposes of this study these interventions have been categorised in to four different categories.

4.4.(a) Step changes

Step changes within athletic improvement occur when a rule change or an introduction of a new technology influences all top athletic performers. Step changes can be modelled by using supplementary parameters in addition to the global improvement function. Gauging the additional parameters allows for the quantification of the step change. If more than one step change occurs, then more step change factors can be applied to the specific years after the step change occurred.

For the potential energy dominant PII, the simple ratio, a step change factor *k* is summed with the global improvement function. The formula for the potential energy PII with the addition of a step change, *c* in terms of raw performance figure is shown in equation 24.

$$PII = \frac{p_1 + c}{p_0} = \frac{p_1}{p_0} + \frac{c}{p_0} \tag{24}$$

The step change factor *k* for this PII ratio is now shown in terms of *c* and p_o, in equation 25.

$$k = \frac{c}{p_0} \tag{25}$$

Finally the PII for the potential energy ratio with the addition of step change factor k is shown below in equation 26.

$$PII = \frac{p_1}{p_0} + k \tag{26}$$

As an example, the javelin has had a number of occurrences where the rules or specifications of a legal javelin have been changed. This has primarily been to reduce the distance and keep javelin throws safe. The main rule change to reduce throw distances in the men's javelin occurred in 1986, and any performances made past this year requires a step change factor, *k*. Equation (23 is modified to give:

$$\mathrm{P} = \left[\mathrm{L} - \mathrm{e}^{-\mathrm{a}\cdot\mathrm{b}^{\mathrm{t}}}\right] + \mathrm{k} \tag{27}$$

For javelin performances made prior to 1986 a normal global improvement function can be applied.

The drag dominant PII ratio (the squared ratio) with an additional step change is formed by the product of *k*, and the global improvement function. The PII with a step change parameter in terms of raw performance *c* is shown in equation 28.

$$PII = \left(\frac{p_0 + c}{p_1}\right)^2 = \left(\frac{p_0}{p_1} + \frac{c}{p_1}\right)^2 = \left(\frac{p_0(p_0 + c)}{p_0 p_1}\right)^2 \tag{28}$$

The PII for this type of ratio can be simplified and is shown in equation 29.

$$PII = \left(\frac{p_0}{p_1}\right)^2 \cdot \left(\frac{c}{p_0} + 1\right)^2 \tag{29}$$

The step change factor *k* for the squared ratio is now shown in terms of *c*, p_0.

$$k = \left(\frac{c}{p_0} + 1\right)^2 \tag{30}$$

In the case for running the introduction of fully automatic timing in the 100 m sprint has had the apparent effect of reducing records of performances. The use of fully automatic timing was compulsory in all international competitions from 1976, but was used for all top 25 times the season before in 1975. This means any 100 m running data needs to be modelled through the use of an additional step change factor *k* from 1975. Equation 23 now becomes:

$$P = \left[L - e^{-a \cdot b^t}\right] \cdot k \tag{31}$$

Figure 4.3 shows the global performance improvement function with a step change in 1975 to account for the introduction of fully automatic timing for the men's 100 metres. *k* from equation 31 can be calculated by fitting the model to available performance data. Note that the years 1973 and 1974 are omitted from this analysis as they contain performances recorded via hand timing methods as well as fully automatic systems.

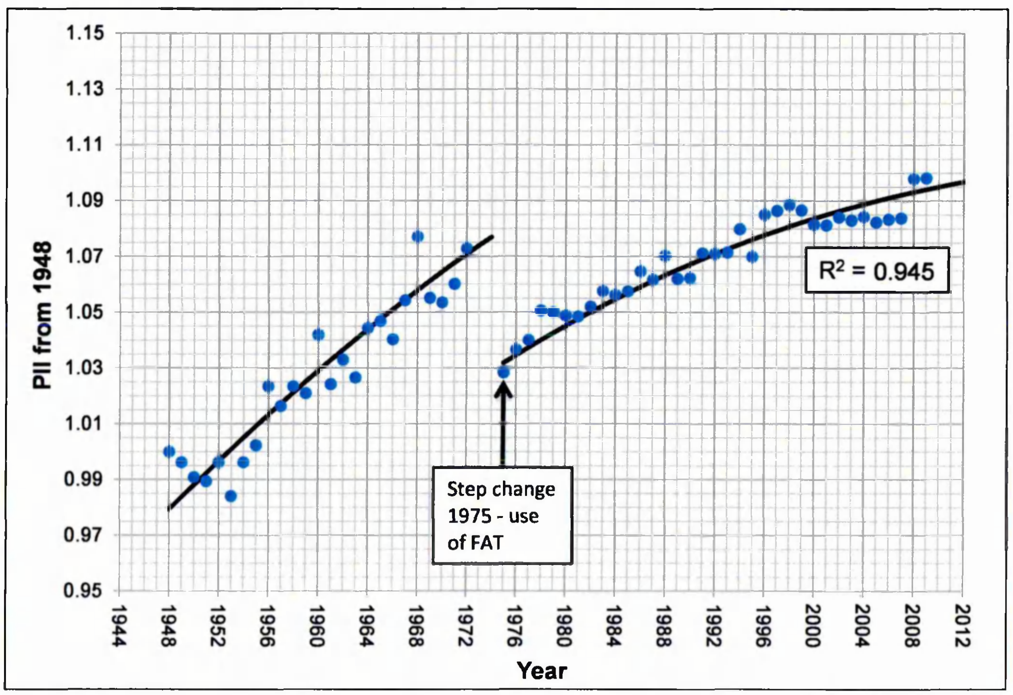


Figure 4.3: Performance improvement index change over time for the 100 metre men with the addition of a global improvement model with a step change in 1976 to account for the introduction of fully automatic timing.

4.4.(b) Linear uptake

The linear uptake model function has been modified from the well-established product/technology uptake theory curve. Shown in Figure 4.4 is the typical product uptake theory curve for a new piece of physical technology that has been introduced to the market place. Level of technology uptake or products sold is plotted against time. The theory behind these curves can be found within various marketing text books (Kotler et al. 2005).

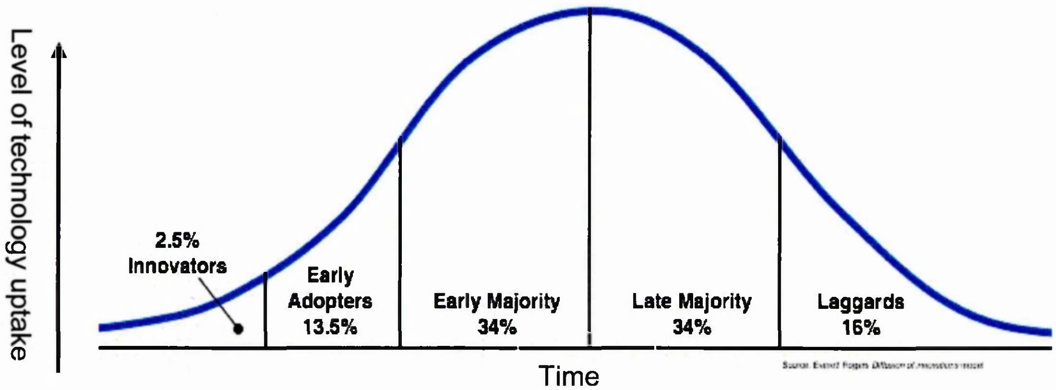


Figure 4.4: Product uptake theory for new products in the market place

In essence any sports technology will conform to the same uptake curve, however if a sports technology is found to improve athletic performance and is allowed to remain within the sport there will not be no decrease in the uptake of this new technology. A saturation point will exist where the new technology has been adopted by all top class athletes and its improvements can be seen within recorded performances. If the introduction of a piece of sporting technology is truly global and instantaneous, and the saturation of the new technology takes place in less than one year, a step change function is required to model this form of intervention, equation 27 or 31. The linear uptake theory will still apply but over a smaller time scale and as performance data examined in this study was a yearly measure any short term uptake periods of less than one year was treated as a step change.

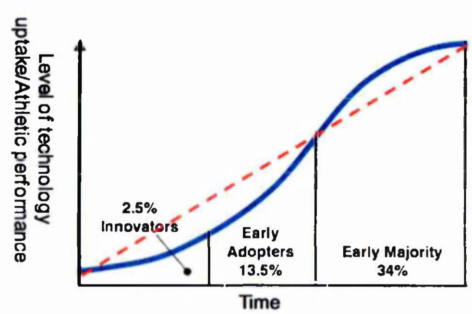


Figure 4.5: Product uptake theory for new sport technology that improves athletic performance shown with linear uptake model (dotted line)

Figure 4.5 shows the first half of the product uptake curve. Assuming that the level of technology uptake is directly related to improvements in athletic performance we can overlay our linear uptake function over the top of the product uptake curve (this is shown in the red dotted line). Modelling the complex "S" shaped nature of this curve can be carried out using more complex functions, but with the low number of data points available this is thought to be too inaccurate, with large confidence intervals for parameters during the modelling stage being derived. A simple linear function will suffice which gives a peak value of the uptake and an indication of the speed of the uptake from the gradient of the line, however it is noted here that the linear function overestimates performance levels at the start and underestimates performance levels at the end of the uptake period. A start and end year is required to allow the function to be fitted to the specific dates. After the linear uptake has reached a saturation point, the performance improvement will continue to conform to the standard global improvement function with one extra term (*linpeak*).

From the start time, t_1 to end time t_2, of the linear uptake ($t_1 \leq t \leq t_2$), the function to model a technology uptake that improves performance over time is as follows:

$$P = \left[L - e^{-a \cdot c^t}\right] + [t \cdot D - \mathrm{lineconst}_1], \tag{32}$$

where D is the gradient of the linear uptake line and $lineconst_1$ is another constant which is equal to $t_1 \cdot D$. The appropriate selection t_1 and t_2 is required and this can be carried out by examining the history of drug abuse within each specific sport.

For t>t2, performances made after the linear uptake period, the equation becomes:

$$P = \left[L - e^{-a \cdot c^t}\right] + \mathrm{linpeak} \tag{33}$$

where *linpeak* is another constant and is equal to $(t_2 - t_1) \cdot D$.

4.4.(c) Modelling drugs with a linear technology uptake

Figure 4.6 shows an example of a linear uptake for possible drug use in the 100 m women's event. This model assumes that drug use started to influence performance figures in this event in 1968 with a linear uptake until 1988. Equation 32 was applied during these periods with t_1 = 1968 and t_2 = 1988 and gradient D was found using the solver function within Excel™. In 1989 the widespread introduction of better drug testing programs may have caused a step change back to original performance improvement trend. This meant that in this example equation 33 was not needed for a post linear uptake period.

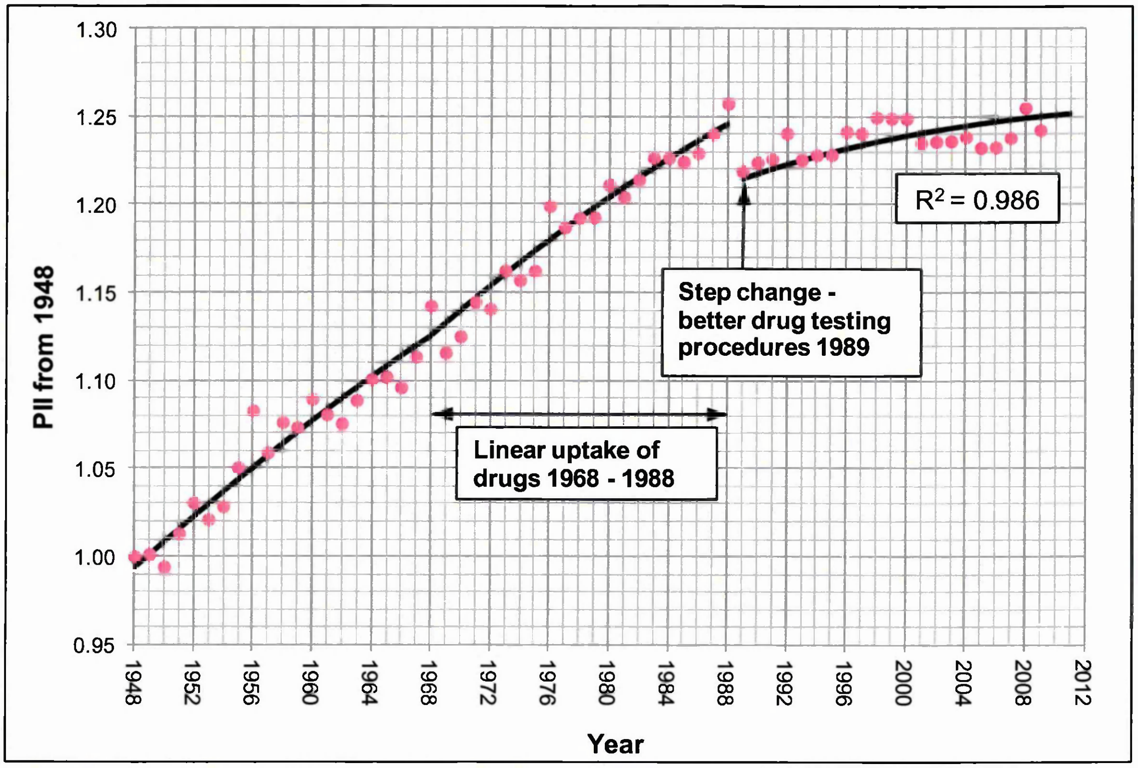


Figure 4.6: Performance improvement index change over time for the 100 metre women with the addition of a global improvement model and drugs linear uptake from 1968 to 1988 and a step change in 1989 for the introduction of enhanced drug testing programs.

4.4.(d) Linear decline

If a technology is adopted over time which is detrimental to sporting performance the exact opposite effect to the linear uptake theory will be encountered. Technologies like this are very rare, and the only known example, is the uptake of drug testing techniques which had the apparent effect of reducing drug misuse within sports. As drug testing technologies became more sophisticated and wide-spread, fewer athletes are able to use banned drugs and avoid detection. The apparent influence of drugs in sport slowly diminished and athletic performance eventually fell to comparable levels before any drug influence commenced.

A specific function has been developed that can be applied to performance data sets with an apparent linear decline in performance after the uptake section for performance-enhancing drugs. The year, at which the linear decline finishes, the performance improvement trend is assumed to revert back to the original global improvement function. This year is another parameter that needs to be selected by examined doping history in each specific sport and has been denoted by the term t_3.

The function for modelling the linear decline in performance after a drugs influenced linear uptake applies to the time period where $t_2 < t \leq t_3$, and is given by the function:

$$P = \left[L - e^{(-a)c^t}\right] + [t \cdot DD - lineconst_2], \tag{34}$$

where *DD* is the linear decline gradient and it calculated using the following formula,

$$DD = \frac{linpeak}{t_3 - t_2}, \tag{35}$$

and *lineconst₂* is another constant which is equal to $t_3 \cdot DD$.

With some sports it may be appropriate to model the linear decline in performance due to the introduction and uptake of better drug testing technologies. Sports that did not see a linear decline period can be modelled through the use of a step change as previously shown in Figure 4.6 where drug testing procedures had an immediate and global effect.

An example of a linear uptake and decline is shown in Figure 4.7. In this example the 100 m women's event was again modelled using a global improvement function but this time with a linear uptake and a linear decline. The start year of the linear uptake was in 1968 (t_1), with a peak year in 1988 (t_2) and the end of the linear decline was in 1999 (t_5).

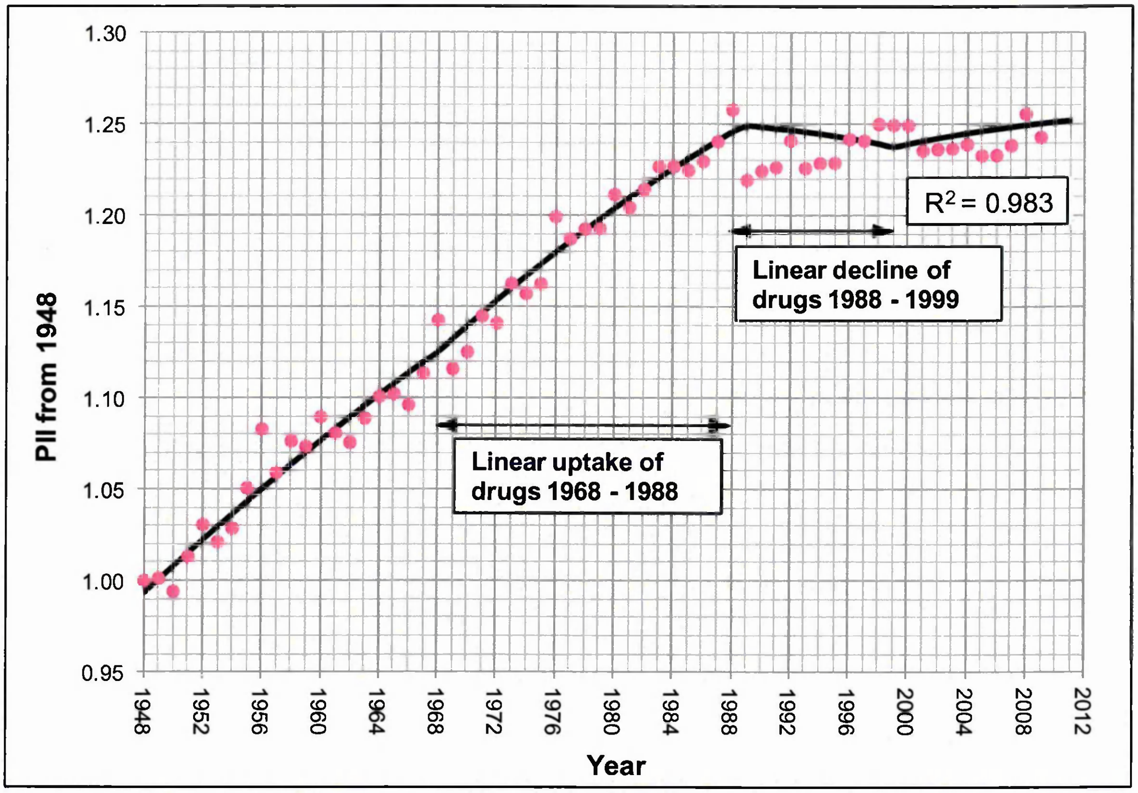


Figure 4.7: Performance improvement index change over time for the 100 m women with the addition of a global improvement model and drugs linear uptake from 1976 to 1988 and detrimental uptake of enhanced drug testing technologies from 1988 to 1999.

4.4.(e) Choice of years for drug interventions

It is believed that the influence of drugs started and ended in different years for different sports. Specific years for the start of the linear uptake and end year of the linear decline could be found by applying different years to the linear uptake models and use the goodness of fit value to find which years gives the best fit. However this is procedure is very complicated as each start year has to be applied individually. Therefore it was decided to use a common drugs uptake start year for all sports, to simplify the fitting of improvement functions. The exact start date of the use of performance- enhancing drugs will never be known, but it is believed that their use started in earnest in the 1960s. The year 1968 was chosen as the common start year for the uptake of performance-enhancing drugs. This was because 1968 was the first year drugs testing procedures were introduced at an Olympic Games, and believed to coincide with a measureable effect. The choice of start year for a linear uptake function does not influence the peak of the linear function, only the gradient is affected. Therefore within this project it is believed that choosing 1968 across all sport for the drugs uptake year will not influence any modelled drug influence. The end year of the drugs uptake is more important and believed to coincide with the introduction of better drug testing procedures in 1989. However not all events are the same and the end of the linear uptake was later customised to coincided with the year when a peak performance figure was found. When a linear decline model was used to model the uptake of better drug testing procedures, the end year for the linear decline was found logically by examining when performance started increasing again following a drugs peak.

4.4.(f) Global championships

Periodic global championships such as World championships and the Olympic Games are also likely to influence athletic performance trends over time (Foster et al. 2011). The largest global athletics competitions are arguably the Olympic Games followed closely by the World Championships. This means athletes may aspire all their lives to produce their best performances during the year of these athletic events. The Olympic Games have a periodicity of four years starting from 1896, whereas the World Championships commenced more recently in 1983 with a periodicity of four years and since 1991 have had a periodicity of two years.

Human athletes cannot perform at their peak for extended periods of time; there is risk of injuries, as well as fatigue. An athlete's primary aim is to perform at the limit of what their bodies can achieve. If they stray beyond this fine line they are vulnerable to injury. To avoid injuries and becoming fatigued athletes conform to periodic training regimes, meaning they peak at times of high prestige competitions like the Olympic Games (Baker et al. 1995; Dick, 2002; Bompa & Carrera, 2005). This implies that during international competition years we are likely to see an increase in measured athletic performance with athletes performing at their peak at these competitions and with heightened competition at qualifying and warm up events throughout that year. In addition to this to maximise performance in these competition years athletes usually take rest years in-between major competitions where they cut down training and competition, which means performances in these years will likely decline.

To see whether this was the case a fast Fourier Transform (FFT) was applied to men's 100 m performance data from 1948 up until 2010 within Matlab^{TM}. The data was completely normalised by only examining the year on year differences in performance so no global improvement trends or interventions needed to be applied. The Fourier transform was used to see whether distinct frequencies occur within a data set. The results of the FFT are shown in Figure 4.8. The maximum of the FFT plot was found at 3.8125 years, approximately the four years of a possible Olympic championship effect. There is also another lower peak at two years, which could indicate another faster frequency oscillation in results which could represent the two-yearly World Championships.

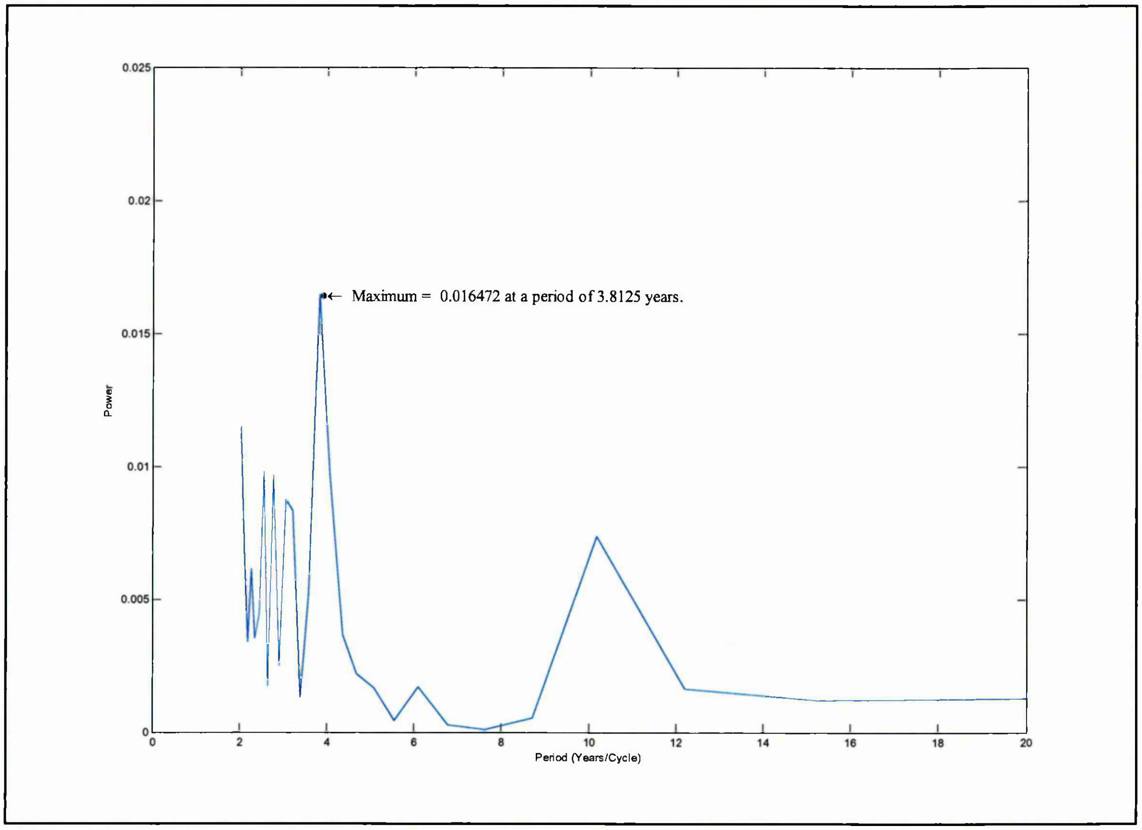


Figure 4.8: Fast Fourier transform results when applied to normalised performance data in the 100 m men's event from 1948 to 2010.

The periodic function which can be used to account for the international competition effect is a sine function, in the form P = A·sin(ωt + φ), where *P* is a performance measure of athletic performance, *t* historical year, *A* is the amplitude of the sine wave, *ω* is the period of the sine wave and *φ* is the phase shift.

A model function can be created that accounts for the periodic fluctuation of athletic performances due to the Olympic Games. A phase shift of π/2 and a period of 4 years is used, as the start year of the performance data examined was 1948, and this is an Olympic year. The model function is given as:

$$P = \left(\left[L - e^{(-a)b^{t}}\right] + \left[A \sin\left(2\pi\left(\frac{100t - 148}{4}\right) + \frac{\pi}{2}\right)\right]\right), \tag{36}$$

where *A* is the amplitude of the Olympic Games sine function and is found through regression analysis. This Olympic function can be applied to the entirety of the data set of the performance data examined.

A similar function can be created for the World Championships. As these only began to take place on a two-yearly basis in 1991, this model can only be applied to data in the year 1991 and after. The function that describes the influence of the Olympic Games and the World Championships after 1991 is given as,

$$P = \left(\left[L - e^{(-a)b^{t}}\right] + \left[A\left(\sin 2\pi\left(\frac{100t - 148}{4}\right) + \frac{\pi}{2}\right)\right] + \left[C\left(\sin 2\pi\left(\frac{100t - 148}{2}\right) + \frac{\pi}{2}\right)\right]\right), \tag{37}$$

where C is the amplitude of the World Championship sine function and is also found through regression analysis. An example of the global improvement function model fitted with a single Olympic function and step change due to fully automatic timing is show in Figure 4.9 for the men's 100 m.

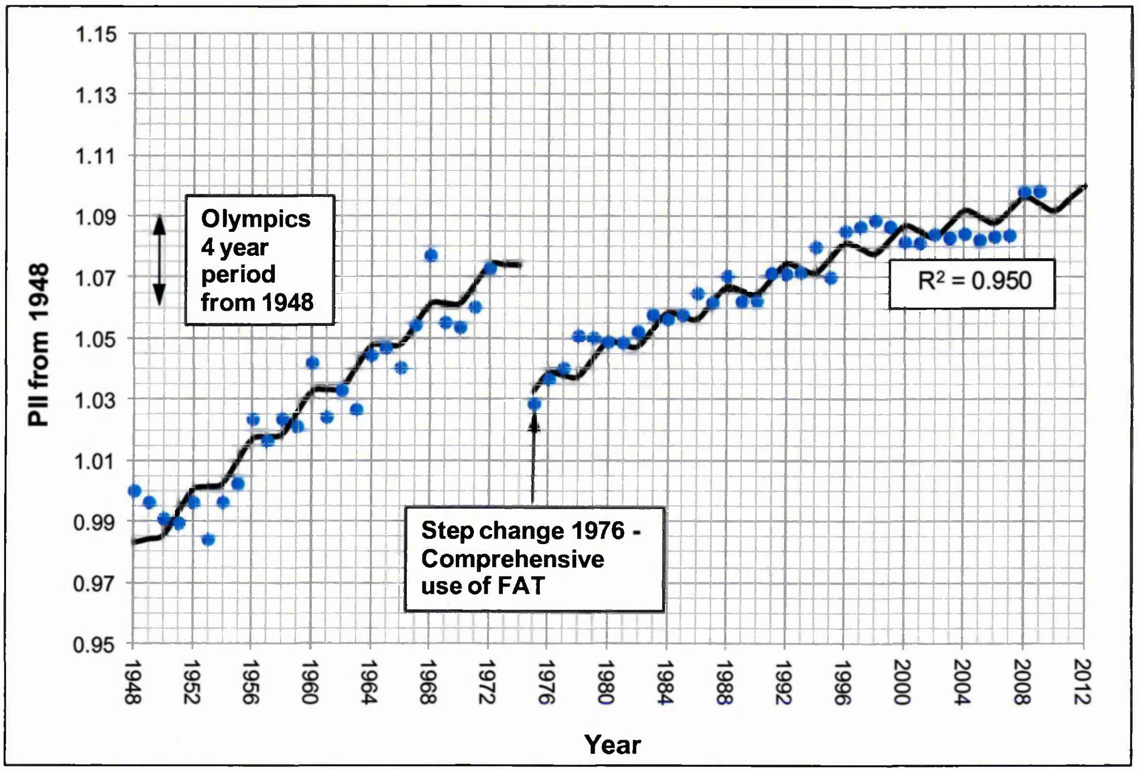


Figure 4.9: Performance improvement index change over time for the 100 m men with the addition of a global improvement model with a step change in 1976 to account for the introduction of fully automatic timing and a single global championship function to model the Olympic effect.

To ascertain whether using a phase shift of $\pi/2$ is appropriate, indicating an Olympic function starts at the start year of 1948, the phase shift of the Olympic function was varied and goodness of fit values recorded. The results are shown in Figure 4.10.

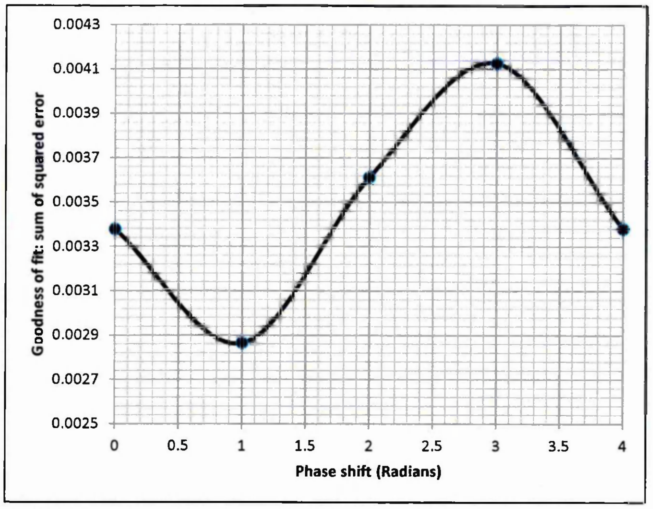


Figure 4.10: Fast Fourier transform results when applied to normalised performance data in the 100 m men's event from 1948 to 2010.

The best fit, lowest sum of squared error was found at a phase shift of 1.57 (2dp) or π/2, which indicates that the Olympic function fits best with the assumption that the start of the performance data set is at 1948 and is a peak Olympic year.

4.5 Chapter summary

The performance improvement index (Haake 2009) is a means to universally gauge performance improvements across a range of athletic sports, and is useful to quantify influencing factors such as technology within athletic development.

Work by Foster et al. (2010) has shown that it is possible to account for hypothesised performance intervention through the use of a common model. A specific exponential function was used to model global population size, but there are many different exponential functional forms which could be utilised to model the other global factors which influence athletic performance. To describe the global improvement trends seen in all athletic events a single exponential function was selected. This selection was based upon specific criteria and a running performance data set.

There are also additional interventions or non-global factors which cannot be modelled through the global improvement function. Firstly there are discrete interventions which occur singularly within a performance data set. These include step changes, linear uptakes and linear declines. The final intervention category is periodic interventions, in which an intervention occurs on a repeatable basis. A periodic function has been utilized to describe the influence of periodic global championships. The functions used to describe non-global influencing factors and the theory behind these functions has been explained and examples given where these functions have been applied to real running performance data.

Chapter 5: Methods III - application of performance models

5.1 Introduction

The theory and justification behind the methods used to examine athletic performance data has been explained in the previous two chapters, however the practical application of these methods has yet to be discussed. Non-linear least squares analysis could be used to fit parameters of the various functions developed to model the different interventions and global improvement trends within athletic performance.

Piecewise or segmented regression analysis may also be required to model different sections of a performance trend. Bounds of the different sections can be defined by the historic date of an intervention's introduction. The specific sections within a performance trend could be treated with different modelling functions to account for the different interventions hypothesised to be present.

The aim of this chapter is to explain the practical application of the performance improvement index together with the fitting of the global improvement function including any additional functions to model hypothesised interventions.

The objectives of this chapter can be broken down in to the following:

1. To explain the processes behind the creation of a performance database.
2. To describe optimisation techniques used in EXCEL™, SPSS™ and MATLAB™ in order to undertake regression analysis
3. To show the development and application of the methods used to model interventions within a bespoke graphical user interface called the "Improvement Function Generator".
4. To explain the fitting procedure for an improvement function to a performance dataset.

5.2 Creation of athletic performance database and application of the performance improvement index

The performance lists created while collecting raw performance figures in section 3.3 were collated into a single spread sheet database for each sport. The database contains field headings of "year", "raw performance figure" and "performance improvement index". Depending on the athletic event, yearly performance improvement index values were calculated within the database according to the required formulas. For field events (potential energy), equation 22 was used and for running, speed skating and swimming (aerodynamic), equation 21 was used.

Each individual event was designated its own sheet within the database. Men's and women's performance data and performance improvement index values were saved within the same sheet and designated specific columns. The format of these performance sheets was standardised and formed the basis of the historic performance improvement index database. This database spread sheets allowed for easy and fast access to any performance figure for any athletic sport and event examined within this study. As the spread sheets are saved in a widely used format, when required the database could be accessed by an external program to extract performance data and carry out any analysis on these performance figures. A screen shot of the performance database is shown below.

	A	B	C	D	E	F	G	H	I	J	K	L
1	Year	Centuries from 1800	100m Males	100m Females	100m Males (s)	100m Females (s)	100m Males (m/s)	100m Females (m/s)	100 m Males Fat adjusted	100 m Females Fat adjusted	100 m fat adjusted Males	100 m fat adjusted Females
2	1948	1.48	1.00	1.00	10.42	12.06	9.59	8.29	1.00	1.00	10.66	12.30
3	1949	1.49	1.00	1.00	10.44	12.05	9.57	8.30	1.00	1.00	10.68	12.29
4	1950	1.5	0.99	0.99	10.47	12.09	9.55	8.27	0.99	0.99	10.71	12.33
5	1951	1.51	0.99	1.01	10.48	11.98	9.54	8.35	0.99	1.01	10.72	12.22
6	1952	1.52	1.00	1.03	10.44	11.87	9.57	8.42	1.00	1.03	10.68	12.11
7	1953	1.53	0.98	1.02	10.51	11.93	9.52	8.38	0.98	1.02	10.75	12.17
8	1954	1.54	1.00	1.03	10.44	11.88	9.57	8.41	1.00	1.03	10.68	12.12
9	1955	1.55	1.00	1.05	10.41	11.76	9.60	8.51	1.00	1.05	10.65	12.00
10	1956	1.56	1.02	1.08	10.30	11.58	9.70	8.64	1.02	1.08	10.54	11.82
11	1957	1.57	1.02	1.06	10.34	11.71	9.67	8.54	1.02	1.06	10.58	11.95
12	1958	1.58	1.02	1.08	10.30	11.61	9.70	8.61	1.02	1.08	10.54	11.85
13	1959	1.59	1.02	1.07	10.32	11.63	9.69	8.60	1.02	1.07	10.56	11.87
14	1960	1.6	1.04	1.09	10.21	11.54	9.79	8.67	1.04	1.09	10.45	11.78
15	1961	1.61	1.02	1.08	10.30	11.59	9.71	8.63	1.02	1.08	10.54	11.83
16	1962	1.62	1.03	1.08	10.26	11.62	9.75	8.61	1.03	1.08	10.50	11.86
17	1963	1.63	1.03	1.09	10.29	11.54	9.72	8.66	1.03	1.09	10.53	11.78
18	1964	1.64	1.04	1.10	10.20	11.48	9.80	8.71	1.04	1.10	10.44	11.72
19	1965	1.65	1.05	1.10	10.19	11.47	9.82	8.72	1.05	1.10	10.43	11.71
20	1966	1.66	1.04	1.10	10.22	11.50	9.78	8.69	1.04	1.10	10.46	11.74
21	1967	1.67	1.05	1.12	10.15	11.41	9.85	8.76	1.05	1.11	10.39	11.65
22	1968	1.68	1.08	1.15	10.04	11.26	9.96	8.88	1.08	1.14	10.28	11.50
23	1969	1.69	1.06	1.12	10.15	11.40	9.85	8.77	1.05	1.12	10.39	11.64
24	1970	1.7	1.05	1.13	10.16	11.35	9.85	8.81	1.05	1.13	10.40	11.59
25	1971	1.71	1.06	1.15	10.12	11.25	9.88	8.89	1.06	1.14	10.36	11.49
26	1972	1.72	1.07	1.14	10.06	11.27	9.94	8.87	1.07	1.14	10.30	11.51
27	1975	1.75	1.03	1.12	10.28	11.40	9.73	8.77	1.08	1.16	10.28	11.40
28	1976	1.76	1.04	1.15	10.24	11.23	9.77	8.91	1.08	1.20	10.24	11.23
29	1977	1.77	1.04	1.14	10.22	11.29	9.78	8.86	1.09	1.19	10.22	11.29
30	1978	1.78	1.05	1.15	10.17	11.26	9.83	8.88	1.10	1.19	10.17	11.26
31	1979	1.79	1.05	1.15	10.17	11.26	9.83	8.88	1.10	1.19	10.17	11.26
32	1980	1.8	1.05	1.16	10.18	11.17	9.82	8.95	1.10	1.21	10.18	11.17
33	1981	1.81	1.05	1.16	10.18	11.20	9.82	8.93	1.10	1.20	10.18	11.20
34	1982	1.82	1.05	1.17	10.16	11.16	9.64	8.96	1.10	1.21	10.16	11.16
35	1983	1.83	1.06	1.18	10.14	11.10	9.87	9.01	1.11	1.23	10.14	11.10
36	1984	1.84	1.06	1.18	10.14	11.10	9.86	9.01	1.11	1.23	10.14	11.10
37	1985	1.85	1.06	1.18	10.14	11.11	9.87	9.00	1.11	1.22	10.14	11.11
38	1986	1.86	1.06	1.18	10.10	11.09	9.90	9.02	1.11	1.23	10.10	11.09
39	1987	1.87	1.06	1.19	10.12	11.04	9.88	9.06	1.11	1.24	10.12	11.04

100m | 200m | 200m (All) | 400m | 400m (all) | 800m | 1500m | 5000m | 10000m | 42195m | LJ | HJ | PV | SHOT | HAMMER | JAVELIN | Discus

Figure 5.1: Screen shot example of the performance database showing fields and data contained, example shown is of the 100 m men's and women's events

5.3 Regression analysis - Optimisation techniques

Regression analysis is a term which includes the various techniques used to model or fit several parameters of a function to best represent the relationship between a dependent variable and at least one independent variable. Therefore human athletic improvement over time can be modelled through regression analysis. Within the analysis athletic performance was treated as the dependent variable and a measure of time, in this case years, was the independent variable. A function that best describes the relationship between human athletic performance and time is required and as explained in the previous chapter, within this study the general form of this function was assumed to be the same for all athletic developments.

5.4 Least squares analysis

The method of least squares analysis is the standard approach to fit parameters of a function to a set of data. In the least squares analysis, the best fit of the model to the data is found when the sum of squared residuals is at a minimum. The residuals are the difference between an observed data point and the fitted value provided by a model function.

Linear least squares analysis is used where the regression model being applied to the data is linear, whereas non-linear least squares analysis is used when the model is non-linear. Linear and non-linear analyses are very similar, in that a non-linear analysis uses a linear model to approximate the non-linear model and then parameters are refined by successive iterations.

5.5 Practical application of non-linear least squares

There are many practical methods in which non-linear least squares analysis can be carried out. Each of these methods have varying degrees of customisation and accuracy. Some methods are highly customisable in that model functions can be specified, where as some methods only have set functions which can be applied to the data. The accuracy of the final solution for best fit parameter values can also vary depending on the accuracy of the optimisation algorithms used to minimise the sum of squares error.

5.5.(a) Excel: Best fit functions on graphs

The simplest method to apply regression analysis is within EXCEL™ using a function within the graph creation tool. Scatter graphs can be created that can plot dependent athletic performance data against the independent historic time data. Lines of best fit or regression models can be applied to the plotted data using the "best fit tool". There are various different functions than can be fitted to the data, but these functions are only limited and cannot be customised. This means any specified global improvement function cannot be applied using this method and not practical for use within this study.

5.5.(b) SPSS modelling of functions within SPSS

SPSS™ version 17.0 is a specialised statics software package that enables complicated statistical methods to be applied to various data sets. SPSS™ has a specific feature which allows non-linear regression analysis to be carried out using fully customisable functions to any data set. In SPSS™ the dependent and independent data can be either typed or imported into SPSS™ by copying and pasting from the EXCEL™ or another data source. In this case athletic performance data was directly copied from the performance improvement database into the software package for non-linear regression analysis to be carried out.

The non-linear regression feature within SPSS™ allows for a fully customisable function to be applied to a data set. This means the global improvement function can be applied to the entire data set (SPSS Regression 17.0, 2009).

It was discovered that SPSS™ cannot read EXCEL™ spread sheets and that the manual importing of data by copying and pasting is a slow process. In addition to this, results (goodness of fit values and model parameter estimates) found when the fitting a function to the data are saved in a non-standard format. Results can be printed out directly but only digitally read by SPSS™, which makes the transferring and displaying of results difficult. Finally SPSS™ treats the dependent variable as a single data set which means it cannot carry out segmented regression analysis. For these reason SPSS™ was only used in a preliminary trial for simple non-linear regression, along with cross referencing results gained by other methods, and not used further in this study.

5.6 Segmented or piecewise non-linear regression

Segmented or piecewise non-linear regression is the same as standard regression, however in segmented non-linear regression the dependent variable is broken down into two of more distinct sections or segments. Within the different segments a specific modelling function can be applied to the data.

In the case of human athletic improvement over time, segmented regression analysis was used to represent different eras of technological development. One segment could be used to model the athletic developments made before the introduction of a technology. A following segment could be used to describe the trends in performance improvements when a new technology is introduced. Finally a third section could be used to describe athletic developments after the introduction of a piece of technology.

It was discovered that the two methods used so far to apply non-linear least squares analysis do not allow for piecewise regression analysis.

This was because SPSS™ or the graphical function in EXCEL™ did not allow for the segmenting of performance data and therefore different models' functions could not be applied separately within these segments. New methods of non-linear least squares analysis were needed to be found which allowed for the breaking up of data sets and hence segmented regression analysis.

5.7 Stepwise regression

Stepwise regression analysis a method of regression analysis used to assess whether additional predictor variables are beneficial to the fit of the model. For the purposes of this study, a forward selection manual stepwise regression analysis will be used to ascertain whether modelling functions accounting for various interventions can be used to model the different interventions.

Manual stepwise regression analysis was carried out at each stage of the fitting process by assessing the change in adjusted regression coefficient, the best measure of goodness of fit of the modelling function.

The forward selection procedure will also be undertaken, where the simplest model is fitted first, followed by models of increasing complexity. This works well as the global improvement function is primarily fitted and then the complexity is increased when modelling functions are added.

Manual forward stepwise regression analysis gives the best opportunity to customise model functions, ideal for the variety of different interventions found within the different athletic events.

5.8 Non-linear regression analysis within – Excel solver – Reduced gradient algorithm

It was found that non-linear analysis can be undertaken within an EXCEL™ spread sheet using the "Solver" function (Walsh & Diamond 1995, Brown 2001). For this study spread sheets were set up to fit custom model functions to performance data and carry out non-linear regression analyses. Columns of performance data were logged along with the year of the performance. A customisable model function was then used to calculate a predicted performance value based upon the year. Parameters of the model were stored at the top of the spread sheet and defined in the model function using absolute function notations. The difference between the models' predicted value and the performance data or observed data was calculated in another column. These values were then squared and also stored in another column. This column was then totalled up and stored in another cell at the head of the spread sheet and was designated "The sum of squares residuals". The best fit of the model function to the data is found when the sum of squares residuals is at a minimum. The 'solver' function within EXCEL™ is an optimisation function, and allows for a target cell to be maximised or minimised by changing parameter cells. The solver function uses a generalised reduced gradient algorithm (specifically GRG2) (Microsoft 2011 and Lasdon 1978) and is ideal for use for non-linear regression analysis. Within this solver analysis the target cell was selected as the sum of squares residuals and was instructed to find a minimum value by changing the other parameters of the function. Best fits of the model functions to the performance data were initially carried out in this way.

Segmented regression analysis was also carried out using this method; however the different sections of the performance data were assigned different model functions. The size and location of the different segments can be changed to meet required specifications and model parameters found using the same method as normal regression analysis carried out with the solver. The solver was requested to find a minimum value of the sum of squares residuals by changing model parameters all the different sections.

This method was easily customisable and allowed for different segments and functions to be fitted to performance data easily. Graphical representation of the fit of the data could also be easily shown using the EXCEL™ graph creation facility; however there were a couple of difficulties with this method.

Firstly this method, although fully customisable, was very slow and cumbersome to apply to multiple data sets using numerous functions. Secondly for more complex functions with multiple parameters, the best solutions were sometimes not found. This was because a simple generalized reduced gradient algorithm was employed by solver to fit model variables to the data.

A faster, more convenient method needed to be identified to carry out non-linear segmented regression analysis for the purposes of this study. It was decided to use the programming language MATLAB™ and available functions within this software package to create a custom graphical user interface where non-linear segmented regression analysis could be carried out.

5.9 Matlab™- non-linear regression

To allow for faster processing, nonlinear regression analysis was carried out using an optimisation function within MATLAB™. The optimisation toolbox within the MATLAB 2009b software package had the capacity to undertake fully customisable non-linear segmental regression analysis.

MATLAB™ contains a number of pre-written functions which can be called within a program to assist with programming tasks such as statistical or image processing problems. For the purpose of this study the optimisation toolbox was utilised. The optimisation toolbox enables a program to draw upon pre-written algorithms to assist with minimising the sum of squares errors during a regression analysis (Mathworks handbook 2010). Initially experiments were carried out using different minimisation functions run within MATLAB™ with imported data from the athletic performance database. A MATLAB™ program was created which utilised the functions within the optimisation toolbox. The steps taken to create this program will now be explained.

5.9.(a) Extraction of performance data from the performance database

Firstly performance data needed to be extracted from the performance database. Both the independent variable (year) and the dependent variable (performance figure PII) needed to be imported. MATLAB™ contains a helpful function which enables data from EXCEL™ spread sheets to be imported and saved to the MATLAB™ workspace as a variable. The path name of the EXCEL™ file, sheet name, column numbers and row numbers are parameters of the EXCEL™ read function and need to be specified within the program.

5.9.(b) Intervention modelling functions

To keep the main program code tidy extra functions were created which could be called by the main program. These functions denote the functional forms, model, parameters and bounds for the various intervention modelling functions. Initially a MATLAB^{TM} function was created which applied the global improvement function to the entirety of the data set. Further intervention modelling functions were created where required, to model the different interventions envisaged in the athletic sports examined. Unique intervention modelling functions were required so that the different equations, interventions modelling steps and bounds could be applied on an event-by-event basis. Additional parameters such as the function bounds/intervention years could be inputted into these intervention modelling functions through the use of global variables when initiating this function in the overall programming code. The following code denotes the global improvement function designated 'Expo', the parameters and the functional form:

```
function IF = Expo(params,x)
L1=params(1);
a1=params(2);
b1=params(3);
```

The code below now shows the simple function which denotes the intervention model that includes the global improvement function along with one intervention for the aerodynamic performance improvement index. This function is designated "Expo_1int"

```
function [IF] = Expo_1int(params,x)
global intyear1year
L=params(1);
a=params(2);
b=params(3);
k1=params(4);

z=length(x);
for i=1:z
    if x(i)<=intyear1year
    IF(i)= L - exp(-a * (b2 .^x(i)));
```

The function is split in two different sections, and the sections defined by the intervention introduction year "intyear1year" which is a global variable. An 'if' programming statement is used in this case to define the different functions within the different sections needed for segmental regression. However 'for' statements can be used in conjunction with multiple 'if' statements when modelling more than one intervention.

5.9.(c) MATLAB^{TM} function: 'fminsearch'

The intervention modelling functions were called within the overall program using specific optimisation functions available with the Optimisation toolbox in MATLAB^{TM}. These optimisation functions contained various algorithms which allowed for minimisation of parameters such as the sum of sum of squares error while carrying out non-linear regression analysis. Initially a simple algorithm was used which minimised the sum of squares error using the 'fminsearch' function. Performance data, the functional form of the model along with initial parameter estimates were fed to the 'fminsearch' function which returned best fit parameters of the model and sum of squares error. 'fminsearch' uses the simplex search method (Lagarias et al 1998). This is a direct search method that does not use numerical or analytic gradients. The following code shows the implementation of the 'fminsearch' function within the overall regression program:

```
%Find the parameters for the exponential curve which minimised SSE
estimates = fminsearch(@Expo_1int,[1 1 1 1],
[],xpre,ypre,xpost,ypost,k);


%Get out fittedcurve1 and fittedcurve2
[sse,fittedcurve1,fittedcurve2] = Expo_1int
(estimates,xpre,ypre,xpost,ypost,k);


%save estimates to workspace
```

The function 'Expo_1int' is called and defines the functional form, parameters and segments of the modelling function. Best fit parameter estimates, fitted curves and the sum of squares error 'sse' are saved once the 'fminsearch' function has been applied. Intyear1year has been defined earlier on in the code and is the year of the intervention introduction. The algorithm that the 'fminsearch' uses does not have the capability to calculate parameter confidence intervals, and was too simplistic for use in this study. It was found that 'fminsearch' often did not find a minimum sum of squares solution unless very accurate parameter estimates were initially fed to the program. A new function was found, called 'nlinfit' and this was more appropriate to model a non-linear function.

5.9.(d) MATLAB™ function: 'nlinfit'

The 'nlinfit' function was next utilised to perform non-linear least squares regression analysis. Specifically, the 'nlinfit' function uses the Levenberg-Marquardt algorithm (Seber 2003, Moré 1978) which is a more complex algorithm specifically designed for non-linear regression problems. 'nlinfit' had the additional benefit in that it could be used in conjunction with another function called 'nlparci' which returned parameter confidence intervals. The algorithm 'nlinfit' employed a more complex optimisation function which meant minimised sum of squared error solutions were found, even when more complex intervention modelling functions were used.

As with 'fminsearch' the same procedure for implementing regression analysis was used with 'nlinfit'. An intervention modelling function was specified and historic performance data along with initial model parameters were specified and applied to the function. Executing the function created the following output data: sum of square error, 95% confidence intervals and best fit curve data. Using additional functions 95% confidence regions, MSE, regression coefficient (R^2) and adjusted regression coefficient (R^2 adj.) were also calculated. The following code shows the implementation of 'nlinfit' in applying the 'Expo_1int' functional form. This is much the same as the 'fminsearch' implementation, but with the addition of confidence intervals calculations and parameter error estimates.

```
%Use nlinfit
[estimates,resids4,J4,COVB4,mse4] = nlinfit(x,y,@Expo_1int,[1 1 1
0.955],[]);
% use nlparci to get parameter confidence intervals
ci = nlparci(estimates,resids4,'jacobian',J4);


%Find predicted y values, 95% confidence
[ypred4,delta4]=nlpredci(@Expo_1int,x,estimates,resids4,'jacobian',J
4);


%Find 95% confidence bounds
ylower = ypred4-delta4;
yupper = ypred4+delta4;
%Feed estimates and x values to return IF
[IF] = Expo_1int(estimates,x);
%Confidence intervals (95%)
halfwidth1 = (ci(:,2) - ci(:,1))/2;


%SSE
sse = sum(resids4.^2);
```

5.9.(e) Goodness of fit values - comparing improvement functions

To ascertain whether an intervention modelling function is appropriate for modelling the trends and interventions seen with athletic performance a goodness of fit measure must be calculated. This value can then be compared between modelling functions and the suitability of the different models can be quantified. Within non-linear regression analysis three typical goodness of fit values are commonly used; these are the sum of squares error (SSE), the coefficient of determination (R^2) and the adjusted coefficient of determination (Adj. R^2). The sum of squares error is the term minimised during the fitting of a model to data, the lower this value the better the fit. If this value reaches zero the model is a perfect fit to the available data. The squared error term denotes that absolute error between the model and the data points. The regression coefficient or coefficient of determination (R^2) is defined as the ratio of the sum of squares explained by a regression model and the total sum of squares around the mean (SST) and is given by the equation,

$$R^2 = 1 - \frac{SSE}{SST} \tag{38}$$

The estimated variance (MST) of the data set is given as,

$$MST = \frac{SST}{(n-1)} \tag{39}$$

where n is the size of the data set (Henry 2001). The estimated error variance (MSE) is calculated by averaging the SSE by dividing the degrees of freedom and is given by the equation,

$$MSE = \frac{SSE}{(n-p-1)} \tag{40}$$

where *p* is the number of predictors in the regression equation (Henry 2001). In the case for PII calculations an additional degree of freedom is lost in this analysis as all PII calculations are all based upon the 1948 data point and this is accounting for by the "-1" in the above equation. The adjusted regression coefficient is finally given by the equation (Henry 2001):

$$R^2{}_{adj} = 1 - \frac{MSE}{MST} \tag{41}$$

The adjusted regression coefficient takes in to consideration the number of variables of the regression model, and does not necessarily increase with an increased number of model parameters unlike the simple regression coefficient (Henry 2001). The adjusted regression coefficient is a better goodness of fit measure and useful for gauging whether an additional modelling parameter within a new modelling function creates a better fit model. If the adjusted regression coefficient does not increase in applying an addition parameter then this parameter cannot be modelled within the overall improvement function as the fit does not increase. Therefore this modelling function can be omitted as it is believed not to exist in the performance data set being examined.

5.10 Confidence intervals and confidence regions parameter significance

Confidence intervals and regions are another check to see whether the intervention model function is appropriate and computes realistic values. 95 % confidence regions are automatically calculated when using the 'nlinfit' function using a bootstrap method and will be utilised graphically to represent the error regions in figures. For all model parameters the 'nlinfit' function also calculates 95 % confidence intervals using the same method. These error parameters can be used to assess the significance of these predicted parameters and thus the gauged intervention size. If error bounds are greater than the modelled intervention size, it is believed that this intervention is not significant and stated in each discussion. Estimations of the 95 % confidence intervals are made through the assumption that the performance data points are distributed normally around the regression model. The confidence intervals are calculated by using the mean squared error (MSE) of the regression model.

5.11 Relating performance improvement index values back to raw performance values

To relate the performance improvements back to raw performance figures in terms of times for race events or distances in field events, addition equations are required. In the case for field events with a simple PII ratio the equation to calculate the intervention size in terms of native performance figures K_{raw} is given by the equation:

$$K_{raw} = K_{pii} \cdot P_{1948,} \tag{42}$$

where K_{pii} is the intervention size in terms of the percentage increase in the PII and P_{1948} is the native performance figure at the base line year of 1948. In the case of the squared PII ratio for race events, the equation relating the size of the intervention back to raw performance values is given by equation:

$$K_{raw} = \left[\left(\sqrt{K_{pii}}\right) - 1\right] \cdot P_{1948}. \qquad (43)$$

5.12 Graphical user interface – Improvement function generator

Up until now, executing the programming code in order to carry out non-linear regression analysis and model fitting was implemented in the MATLAB™ programming environment. Executing the MATLAB™ code meant each time a new model or performance data set was used, lines of code had to be altered depending on the performance data, modelling function or bounds required. This made it time-consuming to implement regression analysis for a large number of performance datasets, model functions and interventions. A graphical user interface or GUI which controls the overall regression program was required to save time and make the regression modelling simpler, faster and easier to implement for the purposes of this project. A GUI was created and was designated the "Improvement function generator" (IF generator). The 'IF generator' is basically a front end which allows changes to be made to the regression program running in the background. It was initially envisaged that performance data could be selected and imported from the performance database, results exported and graphs created. The flow diagram of the inputs and outputs of the 'IF generator' is shown in Figure 5.2. A screen shot of the GUI fitting a standard improvement function to the men's 100 m data from 1948 is shown in Figure 5.3.

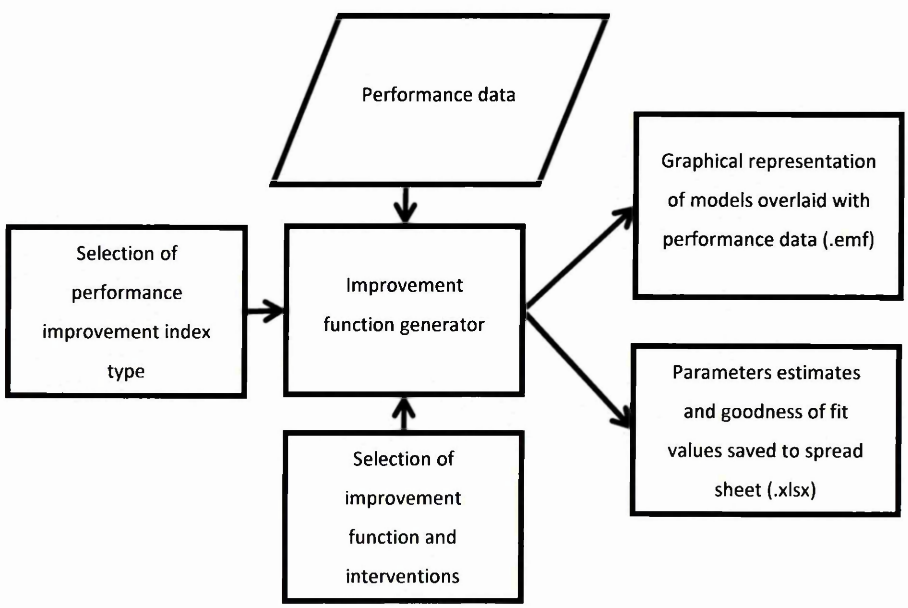


Figure 5.2: Flow diagram denoting the steps required to run the Improvement function generator.

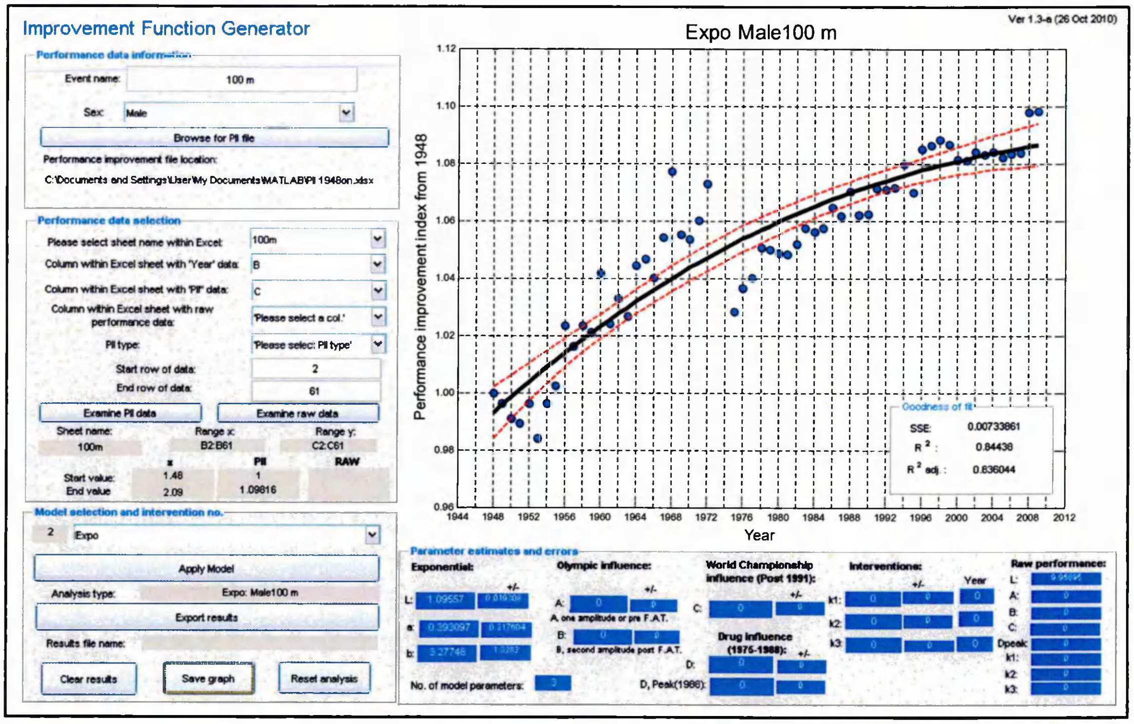


Figure 5.3: Screen shot of the improvement function generator graphical user interface diagram showing an standard exponential global trend analysis.

5.13 Stages of the graphical user interface

5.13.(a) Naming data and selection of sex

Initially the data set being examined is assigned a name; this is usually the name of the event and in the example shown in Figure 5.3 is designated the "100 m". In addition to a name, the sex is chosen of the performance set being examined; this acts additional identification for the analysis and is stored for later use.

5.13.(b) Selection of performance data

Next historical performance data in the form of performance indices are imported to the GUI program from the spread sheet data base of performance figures. A spread sheet is selected and data from a specific work sheet is selected to be imported in to the GUI. The year and corresponding performance figure is selected by an assigned column which can be changed on the GUI. The work sheet from which data is collected can also be changed and acts as identification for each specific event.

5.13.(c) Selection of performance improvement index type:

The type of performance data being saved has also to be selected. This is either an aerodynamic data set in the case of race events or a potential energy type in the case of field events. This selection is saved within the GUI in order to calculate raw performance figures from performance index values.

5.13.(d) Selection of improvement function

The specific improvement function now needs to be selected. This is the type of improvement function that will be applied to the imported performance data. Selection is made from a drop-down list of available functions available; each function having been assigned a model number to help with identification. When a new improvement function is required a new MATLAB™ function is created which is assigned a new model number. The new function can then be called through the GUI and applied to any performance data set. The standard global improvement function (or "Expo") has been labelled "model 2" and is shown selected in Figure 5.3.

5.13.(e) Application of the model

When all input parameters are selected and performance data imported to the GUI the button "apply model" can now be pressed. This then applies the improvement function to the performance data set using the 'nlinfit' function within MATLAB™. Any extra year parameters required for a specific improvement function are called for and typed in by the users, for example the start and end dates of a linear uptake or step changes. In applying the 'nlinfit' MATLAB™ function. A best fit model function, best fit model parameters, confidence bounds (defaulted 95 %) and confidence regions are all saved within the GUI program; these can then be outputted and saved at a later point.

5.13.(f) Other parameter outputs

The sum of squares error is outputted as part of the 'nlinfit' function, however the other goodness of fit values are not outputted. Therefore the regression coefficient and adjusted regression coefficient are calculated separately with additional equations within the GUI programming. The PII outputted are also converted back to raw performance figures to give a better indication of the scale of the different modelled interventions. Depending on the intervention being modelled, performance improvement type-specific functions are used to calculate raw performance figures.

5.13.(g) Result outputs

The best fit model, 95 % error regions is overlaid on to the performance data and displayed on the GUI upon successful application of an improvement function. In addition to this goodness of fit parameters, model parameters and raw performance figures are also displayed within the GUI as depicted in Figure 5.3. The data displayed on screen can be exported with additional programing code. Shown in Figure 5.4 is an example of the standard output graph showing the improvement function superimposed onto a performance data set, in this case the 100 metre men's event.

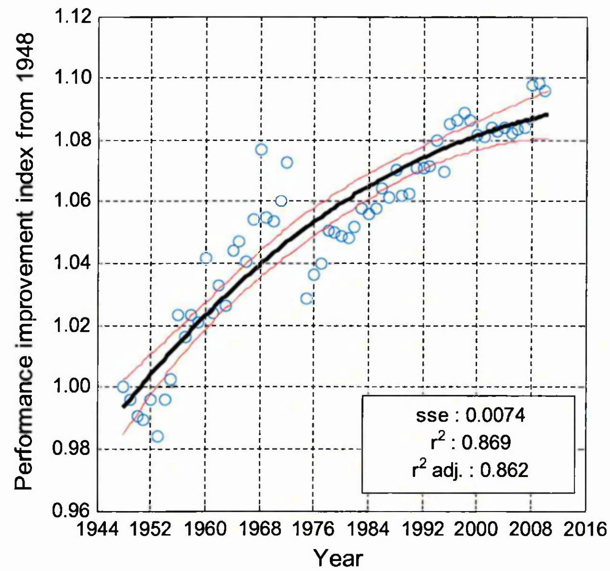


Figure 5.4: Example of an outputted graph of performance improvement index against year, the performance improvement model and confidence bounds for the men's 100 metres with a standard exponential model fitted.

Results can also be exported in a spread sheet format, with addition coding. When clicking the button "export results" all results from current improvement function are exported to a single worksheet and designated a unique name derived from the overall analysis name, gender and improvement function name. An example of the outputted results on one work sheet is shown in Figure 5.5. Results from the application of multiple improvement functions can be saved to a single spread sheet work book under different work sheets. A summary sheet is created at the end of an improvement function analysis by clicking the "create summary" button. The results from the application of the individual improvement functions saved in each work sheet are pooled together into one summary sheet at the end of the spread sheet work book, and example of which is shown in Figure 5.6.

Expo Male 100 m												
Paramete	Predicted	+/-	Year of int	Raw performance value	+/-	Year	Centuries	Raw performance	PII	IF	Upper	Lower
L	1.098276	0.020485		9.946691393	0.092784	1948	1.48	10.424	1	0.993545	1.00237	0.984719
a	0.41602	0.2192		0	0	1949	1.49	10.444	0.996174	0.996225	1.00442	0.98803
b	3.134326	1.22383		0	0	1950	1.5	10.472	0.990854	0.998866	1.00647	0.991262
A (Olympi	0	0		0	0	1951	1.51	10.48	0.989342	1.001468	1.008523	0.994414
B (Olympi	0	0		0	0	1952	1.52	10.444	0.996174	1.004031	1.010579	0.997484
C (WC eff	0	0		0	0	1953	1.53	10.508	0.984076	1.006554	1.01264	1.000468
D (Drugs g	0	0		0	0	1954	1.54	10.444	0.996174	1.009038	1.014709	1.003366
k1 - interv	0	0	0	0	0	1955	1.55	10.412	1.002306	1.011481	1.016787	1.006175
k2 - interv	0	0	0	0	0	1956	1.56	10.304	1.023428	1.013885	1.018876	1.008893
k3 - interv	0	0	0	0	0	1957	1.57	10.34	1.016314	1.016248	1.020976	1.01152
k4 - interv	0	0	0	0	0	1958	1.58	10.304	1.023428	1.018572	1.023087	1.014056
k5 - interv	0	0	0	0	0	1959	1.59	10.316	1.021048	1.020855	1.025206	1.016503
k6 - interv	0	0	0	0	0	1960	1.6	10.212	1.041951	1.023097	1.027332	1.018863
k7 - interv	0	0	0	0	0	1961	1.61	10.3	1.024223	1.0253	1.029459	1.021141
k8 - interv	0	0	0	0	0	1962	1.62	10.256	1.03303	1.027462	1.031582	1.023342
SSE	0.007407	0		0	0	1963	1.63	10.288	1.026613	1.029584	1.033694	1.025473
R^2	0.868736	0		0	0	1964	1.64	10.2	1.044404	1.031665	1.03579	1.02754
Adjusted I	0.861827	0		0	0	1965	1.65	10.188	1.046866	1.033707	1.037864	1.029549
Drugs pea	0	0		0	0	1966	1.66	10.22	1.04032	1.035708	1.039908	1.031507
DD	0	0		0	0	1967	1.67	10.152	1.054303	1.037669	1.04192	1.033417
LU	0	0		0	0	1968	1.68	10.044	1.077098	1.03959	1.043894	1.035285
LD	0	0		0	0	1969	1.69	10.148	1.055135	1.041471	1.045827	1.037114
LUPeak	0	0		0	0	1970	1.7	10.156	1.053473	1.043312	1.047717	1.038908
Event Olympic Start year			0			1971	1.71	10.124	1.060143	1.045114	1.049561	1.040668
						1972	1.72	10.064	1.072822	1.046877	1.051357	1.042396
						1975	1.75	10.2788	1.028452	1.05193	1.056454	1.047406
						1976	1.76	10.2384	1.036584	1.053537	1.058054	1.04902
						1977	1.77	10.2212	1.040076	1.055106	1.059605	1.050606

Figure 5.5: Example of an outputted results sheet for the results gained from the application of one improvement function, in this case the global improvement trend for the 100 m men's event.

100 m Male

PII

	L	+/-	a	+/-	b	+/-	A
Expo Male 100 m	1.098276	0.020485	0.41602	0.2192	3.134326	1.22383	
Expo & 1 int Male 100 m	1.14915	0.016791	0.235472	0.061038	3.939946	0.708361	
Expo & 2 int Male 100 m	1.143298	0.017886	0.224344	0.061158	4.121489	0.793943	
Expo & 3 int Male 100 m	1.145748	0.034267	0.227421	0.072383	4.061186	1.060613	
Expo & 4 int Male 100 m	1.202086	0.091505	0.277016	0.067234	3.159884	0.959746	
Expo,custdrugs&3int Male 100 m	1.172471	0.041868	0.263016	0.072649	3.479281	0.847079	
Expo, Drugs UD 3int Male 100 m	1.165989	0.035421	0.254708	0.071205	3.602863	0.841706	
ExpoOly,DrugsUD3int Male 100 m	1.169559	0.034953	0.25768	0.06686	3.546582	0.77946	0.0033
Expo, DrugsUD3int Oly WC1983 Male 100 m	1.170469	0.03565	0.258501	0.067225	3.532231	0.781444	0.0032
Expo, DrugsUD3int Oly WC1983PP Male 100 m	1.165686	0.031413	0.253306	0.062805	3.615456	0.749113	0.007

Raw data

	L	+/-	a	+/-	b	+/-	A
Expo Male 100 m	9.946691	0.092784	0	0	0	0	
Expo & 1 int Male 100 m	9.724024	0.071051	0	0	0	0	
Expo & 2 int Male 100 m	9.74888	0.076269	0	0	0	0	
Expo & 3 int Male 100 m	9.73845	0.145708	0	0	0	0	
Expo & 4 int Male 100 m	9.507508	0.363179	0	0	0	0	
Expo,custdrugs&3int Male 100 m	9.626831	0.17202	0	0	0	0	
Expo, Drugs UD 3int Male 100 m	9.653551	0.146716	0	0	0	0	
ExpoOly,DrugsUD3int Male 100 m	9.638809	0.144112	0	0	0	0	0.017
Expo, DrugsUD3int Oly WC1983 Male 100 m	9.635059	0.146816	0	0	0	0	0.0169
Expo, DrugsUD3int Oly WC1983PP Male 100 m	9.654806	0.13015	0	0	0	0	0.0378

Figure 5.6: Example of an outputted results summary sheet for the results collated from the application of multiple improvement functions within one analysis for a specific event. In this case the global improvement trend for the 100 m men's event.

5.14 Modelling stages: Ascertaining the suitability of each model using a manual stepwise regression

A routine was developed to analyse the different interventions within the different athletic sports. The routine is as follows:

(1) Analyse the history of the sport from 1948 and pick out key dates for interventions
(2) Develop Improvement functions to model these interventions on those specific dates
(3) Analyse whether these interventions can be modelled:
    a. Improvement in fit
    b. Realistic parameters gained

Firstly by examining the history of the different sports, major interventions were mapped on to a timeline. To account for the various sporting interventions, modelling functions were created depending on the type of intervention and when it occurs.

To examine whether an intervention can be realistically modelled within an improvement function, a manual stepwise regression analysis was undertaken. A manual method was used as this gave the greatest scope for customizing each improvement function for each specific sport.

A manual stepwise regression routine was developed to analyse whether an additional function increased the goodness of fit of the overall improvement function. At every step the adjusted regression coefficients were collected and an increase in this value indicated a better model fit based on the degrees of freedom of the model. Every fitting step increased the complexity of the improvement function, but did not necessarily increase the goodness of fit. For the different sports a unique routine was developed based on the historical developments within that sport. All fitting steps were applied to each event and a final summary created which mapped the change in adjusted regression coefficient. A final improvement function for each event within the different sports was then created based upon the interventions which could be modelled. Additionally, if a parameter was found to be unrealistic i.e. there was a negative drugs effect, then this modelling step was also left out from the final improvement function. The general order of the fitting routine of manual stepwise regression for all sports is as follows:

(1) Global improvement function (exponential)
(2) Event specific interventions
(3) Drugs interventions
(4) Global interventions, (Olympic and World Championships periodic functions)

The method of modelling interventions within an overall improvement trend is novel and there are no previous examples of this having been carried out before. Therefore it is not known what the most efficient order is in which model the various interventions. For this study the global improvement or exponential function is always fitted first and is used as a base function. Following this sport and event specific functions are fitted; these are usually the largest interventions within the sport. Following this drug interventions are applied and then finally global periodic functions are applied i.e. an Olympic function. This order was the most logical and was kept the same throughout this project for continuity reasons. Following the global improvement function, the next largest sport specific intervention was modelled, and so on until finally all interventions were applied. Drug interventions are dependent on sport-specific interventions and therefore will always be modelled after the sport-specific interventions. In the example of the 100 m men's sprint event, if any drugs functions are fitted before a step change that accounts for fully automatic timing in 1975, drug effects are found to be negative and unrealistic. It has also been found that the order in which the apparent interventions are applied always increases the goodness of fit value. Additionally it has been found that the change in adjusted regression coefficient is unaffected if global functions like the Olympic or World Championships are fitted at the start of end of the fitting procedure. For continuity global functions are always added at the end of the fitting procedure when all other interventions have been accounted for.

A final improvement function tailored to each athletic sport will then be applied after the goodness of fit and other parameters are assessed for suitability. This accounts for all interventions believed to be apparent. The size of the interventions modelled will then be gauged from parameters from this final improvement model.

The order of which improvement functions are applied is believed not to influence the goodness of fit values and subsequent judging the suitability of the model. To see if this is the case the 100 m freestyle swimming event was examined, with 3 step change interventions to account for a possible swimming suit effect tin 2008, 2009 and 2010, as well as a periodic Olympic effect. In applying a standard global improvement trend, the exponential decay function, an adjusted regression coefficient was found to be 0.9802 (4dp). The order at which the Olympic function is applied was changed from the last intervention to be modelled to the first, and the effect of the increase in adjusted regression coefficient mapped. The results are shown in Figure 5.7.

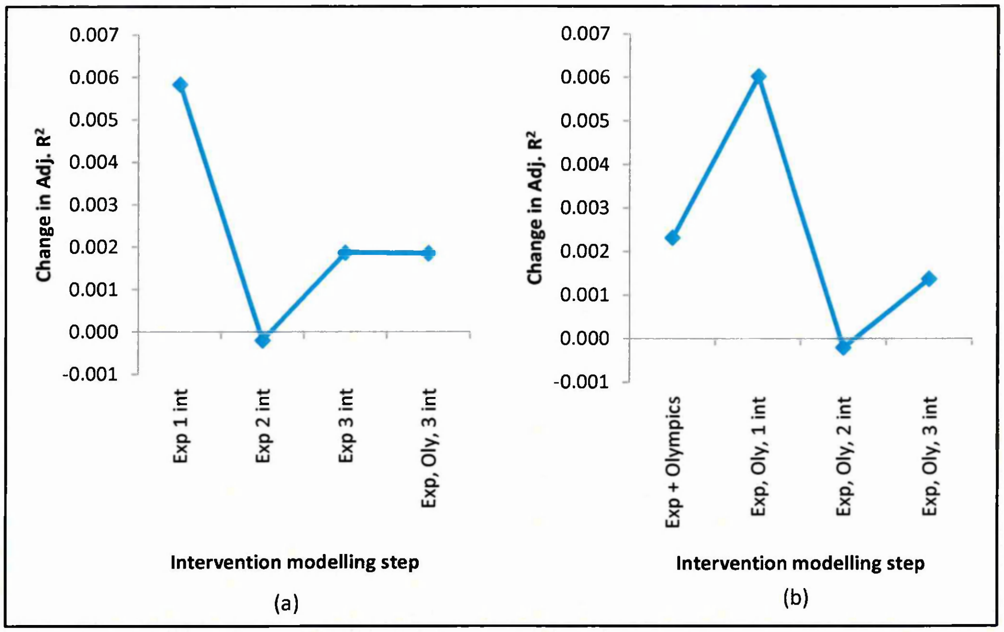


Figure 5.7: Change in adjusted regression coefficient in applying various modelling steps to the 100 m freestyle with (a) Olympic function added last and (b) Olympics function added first

It appears intervention 1 increases the goodness of fit to the greatest extent in both examples, with an increase of about 0.006 in the adjusted regression coefficient, whereas intervention 2 does not increase the goodness of fit values in both cases. The Olympic Games intervention model increases the fit of the function by 0.002 in both cases. Therefore the conclusion can be made that the order in which the interventions are applied is not significant.

The adjusted regression coefficient will be plotted for each modelling step applied to the performance dataset examined for each sport as shown Figure 5.7

5.15 Final improvement function model creation and application

A final improvement function will be designed to fit each specific event and sport. If a function to model a specific intervention is found not to improve the goodness of fit value, the modelling function for that specific intervention is omitted from the final improvement function in that particular event. This means that only interventions that can be seen to improve the fit of the final improvement function will be quantified. In addition to this, if any parameters are found not to model the desired intervention, for example if a negative Olympic effect or a positive drug testing intervention is seen, the intervention modelling step which produced the abnormal parameter is also omitted from the final improvement function. The final improvement functions will be created within MATLAB, accessed within the GUI and applied to the different performance data sets. The magnitude of the interventions found in that particular event will be gauged from this final improvement function.

5.16 Collating results for each intervention seen

When the final improvement function was applied to the performance dataset results were once again exported to a single spread sheet for each event. The results were then collated together for each sport and magnitudes of interventions (PII and raw figures) and error values were represented in graphical and tabular form. These graphs could then be used in the following results sections to examine the size of the various interventions modelled.

5.17 Chapter summary

The performance data collected for the purposes of this study has been collated into a database and the performance improvement index applied to all data. This data can be subsequently accessed by other programs to apply regression modelling techniques. Non-linear regression modelling is the fitting of a non-linear function to a dataset and is required to fit the improvement functions derived in the previous chapter to various datasets. The technique of piecewise non-linear regression is specifically required to model the different parts of an improvement function, in applying different function to performance data before and after an intervention influence is believed to occur. There are various software packages that are capable of performance non-linear regression analysis; SPSS™, EXCEL™ Solver and MATLAB™ are the software packages examined within this study. As MATLAB™ allows for fully customisable functions to be applied to different datasets it was chosen as the preferred method of non-linear regression analysis in this study. Specifically the 'nlinfit' function was utilised to perform non-linear regression analysis. The 'nlinfit' function calculated various best fit model parameters error bounds and regions. In addition to this, results could be represented graphically with graphical function in MATLAB™. Goodness of fit values like the adjusted regression coefficient had to be calculated with separate equations.

The use of MATLAB functions was made simple with the creation of a graphical user interface called the 'improvement function generator'. Performance data could be imported and various improvement functions applied to the data. Results could then be exported in graphical form and tabular form in spread sheets.

A final improvement function is created for each specific athletic event depending on the intervention modelling functions found to improve the goodness of fit. It appears that the order in which each modelling function is applied to the data does not influence whether the intervention improves the fit or not, however it was decided that the largest known intervention will be modelled first for each different athletic event.

Chapter 6: Track events - Running

6.1 Introduction

There are many factors that are likely to influence human athletics performance, technological advances being only one of these. A understanding of the influence each individual factor has on human athletic performance is required before the entirety of influencing factors including technology can be quantified.

Running is believed to be one of the purest sports in the sense that there is little or no influence from interventions such as technology. The factors that are believed to influence running are also believed to influence other athletic sports, and as a starting point it was decided to examine running performance to understand and quantify these universal influencing factors.

The performance improvement index could potentially be used as a means to normalise performance data, make comparisons between different running events and in future compare different athletic sports. This chapter questions the practicality and usefulness of using the performance improvement index for these purposes.

The aim of this chapter is therefore to apply the methods developed in chapters three, four and five to gauge the magnitude of different influencing factors upon running performance. The aim of the chapter has been broken down in to the following objectives:

1. To explore the history and interventions in the athletic sport of running
2. To apply the Performance Improvement index to collected running performance data
3. To apply intervention modelling techniques to running performance data
4. To display results, goodness of fits and magnitudes of interventions
5. To explain the interventions seen in the sport of running

6.2 Running

As mentioned previously, since humans evolved to become a bipedal species, bipedal locomotion at high speeds has been critical for human survival. Human locomotion is also referred to as human gait, and there are many different forms of human gait movements, for example crawling, walking and running. Fascination of the human gait can be traced back to antiquity, with kinematic inspired drawings on Greek vases of sprinting, striding and jogging show below in Figure 6.1 (a), (b) and (c) respectively.

Running competitions requires very little external technologies. Starting and judging running performances requires the use of some technology, but essentially any running competition only requires more than one athlete and a piece of land to compete. Due to the "pure" nature of running events, and the initial belief that running is not significantly influenced by external factors such as technology, this was the first athletic event to be examined.

(a) (b) (c)

Figure 6.1: Greek artist depiction of human gait on the side of vases for (a) competitors sprinting (Young 2009), (b) Striding and (c) competitors jogging (Papakyriakou 1997)

6.3 History of running and other athletic competitions

Achieving a maximum performance of the human gait, i.e.gaining the fastest time for completion of a set distance, has been the domain of competition runners for centuries. Running competitions across the globe had their origins in ancient religious festivals, and such events predate written history. One of the earliest records of competition running comes from the Tailteann Games, which was an Irish sporting festival in honour of the goddess Tailtiu and dates back to 1829 B.C.E. The Ancient Greeks also held athletics competitions, the Ancient Olympic Games with records going back to 776 B.C.E. At these gatherings running competitions played an important focus. After the Greeks and Romans it is not until the 17^{th} century that we find records once again of running competitions, at such events as the "Cotswold Olimpick Games" in England and the L'Olympiade de la République in France.

The codification of running events occurred like many other sporting events in England in the 19^{th} century and this was the modern era of athletic competitions. Athletic competitions consisted of track or running events alongside field events. Athletics competitions were held throughout England, within public schools, military establishments as well as in national competitions between universities such as Oxford, Cambridge and Exeter. Arguably the first example of an international athletic event were inter-university competitions, an early example being an athletic meeting in 1894 between the universities of Yale and Oxford. Typical voyage times across the Atlantic were approximately two weeks meaning international competitions were rare during this century (Page 1911).

Truly global athletic competitions began with the modern summer Olympic Games which started in 1896 in Paris. Running events were a large part of these initial games with events ranging from the 100 m up to the marathon. This is reflected in the modern Olympic motto: “citius, cltius, fortius’”which translates in English to “faster, higher, stronger”. Running events would appear to fall into the first category, in that athlete strive to complete running races faster than their counterparts. Modern global running competitions like the Olympics enable the best human athletes to pitch their primitive running ability against one another, and there is range of modern running events in which athletes are able compete (IAAF 2011).

6.3.(a) 100 metre sprint

The 100 m sprint is the shortest outdoor race and has become the purest expression of human speed. The race was originally run on grass or cinder tracks over 100 yards (91.44 m). Later, the standard metric distance of 100 meters was adopted. The 100 m was one of the events at the inauguration of the modern Olympic Games back in 1896. The IAAF officially sanctioned the use of starting blocks in all sprinting events in 1937. The following year in 1938 the IAAF stipulated that no official record could be ratified without a wind gauge reading. The maximum tailwind permitted has remained 2 ms^{-1} for the 100 m. In 1976 electronic timing was made compulsory at all major competitions and then the following year, the IAAF decided to only accept, electronically recorded times as world records (IAAF. 2011).

6.3.(b) 200 metre sprint

The 200 m sprint is similar to the ancient Greek Olympic event the "stadion" which was a sprint race the length of an ancient Greek stadium. The Stadion length was approximately 180 m, but varied from stadium to stadium (Gardiner 1965).

The 200 m went through many different variations; in the USA the 200 m was originally run in a straight line, before a full bend on a 400m track became universally accepted in 1958.The 200 m event was first seen at the 1900 Olympic Games.

6.3.(c) 400 metre sprint

The longest of the sprint events, the 400 m is sometimes called the endurance sprint event. 400 m is equivalent to a quarter mile or 440 yards. The 400 m was first seen at the Olympic Games in 1896 and like all sprint events is run in lanes.

6.3.(d) 800 metres

The 800 m is the first middle distance event that requires a mixture of both speed and endurance from competitors. It was first held at the 1896 Olympics for the men and 1928 Olympic for the women. The 800 m distance related to the half mile or 880 yards. In 1959 the IAAF decided to act against the frequent jostling in this event by running the first 300 metres in lanes. Today's rules stipulate that, in certain major competitions, the first 100 metres will be run in lanes (IAAF 2011).

6.3.(e) 1500 metres

The 1500 m is a slightly longer middle distance event and was originally run on the 500 m tracks of continental Europe. It is equivalent distance to the English mile event and was first raced at the Olympics in 1896 for men and in 1972 for the women.

6.3.(f) 5000/10000 metres

The 5000 m and the 10,000 m are both metric adaptations of the 3 miles and 6 miles respectively. These events have longer durations and a run at slower average speeds. The 5,000 m was first seen at the 1908 Olympic Games and the 10000 m was seen at the following non official Olympic Games in 1906. Women originally ran a slightly shorter distance of 3,000 m, which started in Britain in 1953. World records in the women's 3,000 m were only accepted in 1974. The 5000 m replaced the women's 3,000 m in 1995. Events of the 10,000 m for the women started up in the 1960s, but it was not until 1981 that world records in this event were recognised by the IAAF.

6.3.(g) Marathon

The marathon is the longest official international athletics federation running event. The marathon was a flagship event at the first modern Olympic Games in 1896 and was an adaptation of the run of Greek messenger Pheidippides back in 490 B.C. The original length of the Marathon was approximately 40 km, but this was later changed in 1908 to 42.195 km for the London Olympic Games. The London distance of 42.195 km was later adopted as the official marathon distance from the 1924 Olympics in Paris. For women the Marathon event at the Olympic Games only started in 1984; however women were running the marathon decades before.

6.4 Interventions in running events

From 1948 there have been many external influencing factors that have contributed to the performance levels in running events. What are believed to be the factors with the greatest influence are shown in Figure 6.2.

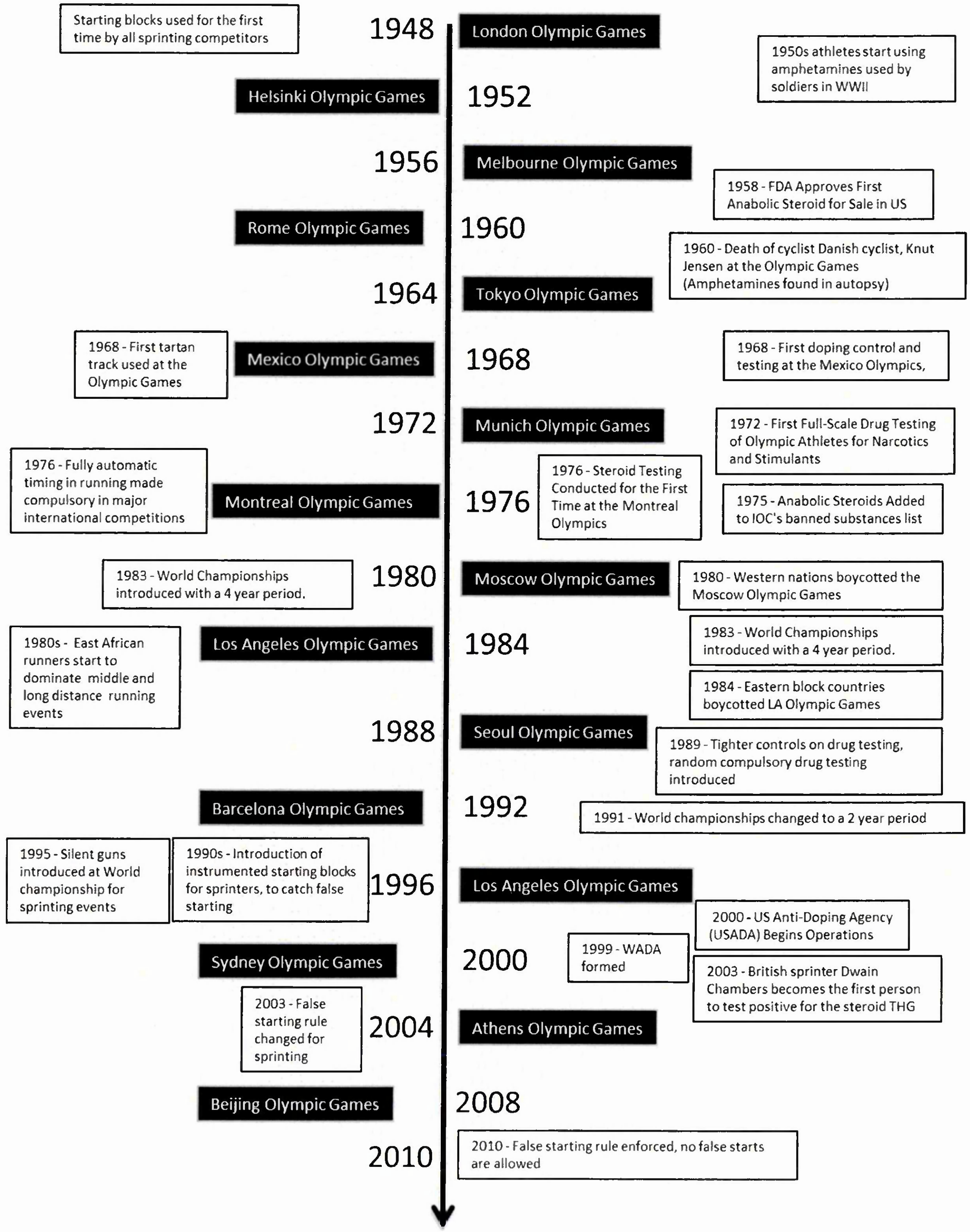


Figure 6.2: Time line of historic interventions to athletic track events from 1948

6.4.(a) Starting blocks

Starting blocks are a physical piece of technology used in sprint races from 60 m up to 400 m including hurdling events. They are a tool for sprinters to get the best start possible. This is done by giving the athlete a platform from which to push off, from which they can exert high levels of horizontal force without the fear of slipping.

The Greeks at the ancient Olympic Games held an event called the Stadion which was a sprint race held the length of the stadium. Competitors would run down the track and to a post and then return. Even in this early athletic event there was the use of technology. Archaeological evidence has shown that starting stones with groves s where runners would put their feet were used for at the start of these Stadion races (Gardiner 1965). This could be an early incarnation of the modern starting block enabling athlete's better grip off the line. Another piece of technology used in these early Stadion events was a Husplex. The Husplex was a starting gate preventing false starts and is similar to B.M.X. start gates, where a barrier that drops when the race starts.

Traditionally sprinters started from a standing position right up until 1887, when Charles H. Sherrill from the United states of America dug small foot holes in a track and tried a crouch start (IAAF 2011). Essentially these holes gave the sprinter a horizontal platform from which to push off from. Stating holes or marks were the origin of the phrase “On your marks” said by starting officials at the star of a race . Modern starting blocks were thought to be invented by Charles Booth in Australia in 1921 (Blackwell 2008). He invented a T-bar with two blocks of wood as places to push off with your feet. Charles Booth used to train on dog tracks and the starting holes he used were injuring dogs. His starting blocks alleviated this problem and now many years later are common place in elite sprint events. 1948 London was the first Olympic Games where starting blocks were used by all athletes in the 100 meter sprint race. Shown below in Figure 6.3 is a screen shot of the start of the London 1948 100 m final.

Figure 6.3: Screen shot taken from – “London 1948, moments from the official movie” (Olympicstube, 2008)

The IAAF officially sanctioned the use of starting blocks in 1937 and since 1978 they have been compulsory for races of 400 m and below in distance, whereby the starting blocks are part of the starting and timing system. The influence of starting blocks cannot be gauged within this study. This is because starting blocks have only been extensively used from 1948 and performance data prior to this date has been excluded in this study. This means running performances made without the use of starting blocks are not available for comparison.

6.4.(b) Fully automatic timing

Fully automatic timing, or F.A.T is a form of race timing where a timing clock is automatically activated by a starting device, and the finish time is either automatically recorded, or timed by analysis of a photo finish. F.A.T. systems used crystal oscillators such as Quartz to gain a higher level of accuracy over traditional clockwork stop watches. F.A.T. was made compulsory and used as official time measurements from 1976 onwards for all international track races. However various systems of F.A.T. were in existence and in use from the late 1950s. The 1968 Mexico Olympics saw the first use of a F.A.T. system for official timing figures.

6.4.(c) Track surface changes

Modern running tracks are made from synthetic rubber materials and it was in the 1968 Olympic Games where a "Tartan" (Polyurethane) track was first used. Tartan tracks came about from the need of an all-round performing track that would withstand rain and be more durable. Performance increases from these tracks was an additional bonus. Recent developments to the compound by track manufactures have been claimed to produce even faster running tracks (Tartan 2007).

The compliance of a running track could also influence running performance. The compliance of the track governs how much deformation under impact loads the track surface undergoes. A compliant or "springy" track surface is more comfortable to run on however when running on a "springy" track time spent rebounding from the surface is increased and hence the runner is slowed down. A non-compliant hard track surface is widely thought to be a faster. This is because there is less energy loss in the transfer of forces between the runner's foot and the track surface. However this is not the fastest track surface. A compliant running track has been found to act like a spring, and if this spring is tuned to the mechanical properties of a human runner speed can be increased. Hence there is a specific intermediate track compliance at which running speed is optimized (McMahon and Greene 1978). Footsteps on an optimized track surface would deform the track to such an extent that it stores energy in the form of elastic strain energy. This energy can then be transferred back to the runner for upon lifting off the track. These optimized tracks are called tuned tracks (McMahon and Greene 1979).

Since the 1968 Mexico running track, "Tartan" tracks have become widespread, however is there evidence in result statistics that show how much these newer tracks have influenced running performances?

6.4.(d) Performance-enhancing drug uptake 1960s onwards

Performance-enhancing drugs can be looked upon as another technology that has possibly improved sporting performance. Drugs are chemical substances that are taken by an individual and have specific physiological effects. The use of many performance-enhancing drugs are prohibited by the rules of competition, but it is well known that the use prohibited drugs was once widespread. Due to the secretive nature of drugs in sport it is hard to ascertain what drugs are being used, by which athletes and what affect they actually have on athletic performance. This makes it difficult to gauge how much drug taking actually improves performance (Golberg et al. 2003 & Tout et al. 2004).

6.4.(e) Clamping down on drugs 1989/2000

To combat the use of proscribed performance-enhancing drugs, technologies have been developed (usually by the creators of the drugs) to test athletes. Accompanying drug testing technology has been the development of testing routines instigated by WADA and national governing bodies of particular sports. These technologies introductions may have had a negative effect on running performances and will be attempted to be modelled (WADA 2011).

6.4.(f) Influx of new competing population

The influx of runners representing East African countries has gone hand in hand with a large increase in performance in middle and long distance events. Runners representing East African countries in middle and long distance events only started to appear in earnest within the top 25 lists in the 1980s. Analysis has shown that prior to this decade there were relatively very few runners in middle and long distance running events that represented East African countries. Evidence for this is shown in Figure 6.4 where the number of runners representing African countries in the top twenty five performance lists has been plotted against historic year. We see that in from the 1980s onwards there is a steep rise in African runners in all events examined. It appears that in 2010 the Marathon, 10,000 and 5000 m events nearly all of the male athletes in top twenty five performance lists are runners representing African countries.

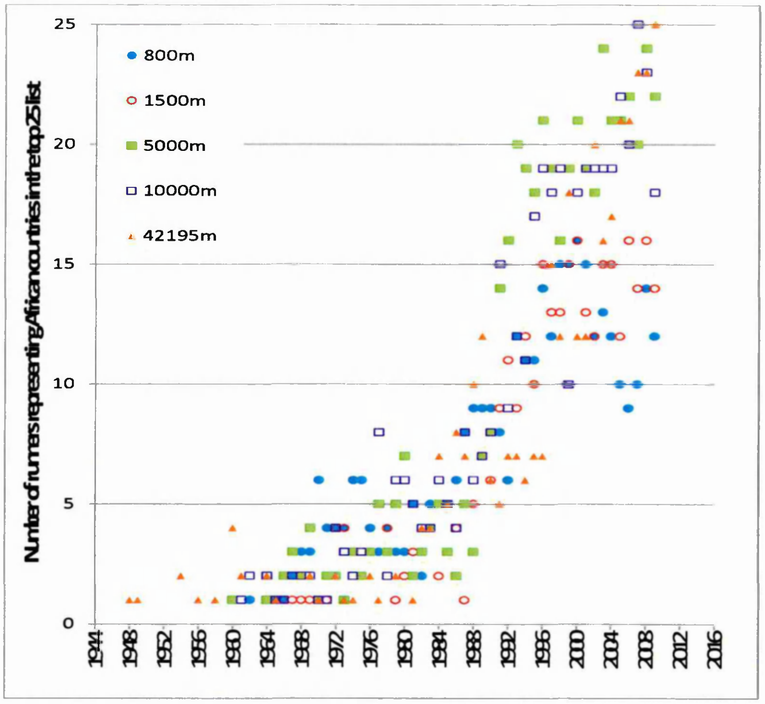


Figure 6.4: The number of runners representing African countries in men's middle and long distance running events against historical year

Many reasons have been proposed for why runners of East African descent have come to dominate middle and long distance events. The first possibility is the environment that the African athletes live and grow up within. There is a lot of evidence which suggests that the human body adapts to the environment in which they live. Environmental determinism is a term used to describe this adaptation and subsequent change in performance of the human body (Hamilton 2000). As many East African runners live at high altitude where there is a lower oxygen density compared to sea level, and predominantly only run/walk to and from work or school throughout their lives. There is a belief that this improves their sea level running performance through adaptions to the lower oxygen density environment (Brugniaux et al. 2006, Clarke et al. 2007). However, other populations which live in high altitude countries such as Nepal, Mexico or Peru do not appear to produce as many world class distance runners as East African countries. This means there must be other contributing factors which allow for East African runners to dominate long distance running events.

Another reason for East African runner dominance could be down to social conditions. There is a drive for many East African runners to leave the poverty and poor living conditions they experience while growing up. Running at an international level is seen as one of the only ways to do this, which may in turn drive potential athletes to train their hardest and pushes up running performance (Hamilton 2000).

Finally there is there is the possibility that differences in an African runner's physiology give them an advantage. Runners with recent African decent or certain genes are believed to possess physiological attributes which enable their bodies to be inherently more efficient at running over long distances (Western et al. 1999, Western et al. 2000, Larsen 2003). These physiological traits could be as a result of living at high altitudes and these variations are just part of the diversity of humans and variations in traits between populations.

The reasons why African runners currently out-perform many other competing nations at running in middle and long distance events are not fully understood and could be a mixture of all of the previously mentioned reasons. Regional domination of athletic events is not new as Scandinavian countries used to dominate the same running events in the mid-20th century. However there is clear evidence that the influx of East African runners has increased the performance in middle and long distance running events but can the effect be modelled?

There could be many reasons for the uptake of African runners in the middle and long distance running event from the 1980s onwards. The main hypothesised reason is that African countries prior to 1980 may have not had the money or resources to train and send athletes to major competitions. Only after the 1980s with the advent of fully commercialised sport and professionalism did African runners have the opportunity to compete on a world stage.

This is also believed to be the case for all sprinting events, with the number of runners specifically of West African descent now dominating the top twenty five lists. The last Caucasian to win a Gold medal in the 100 m at the Olympic Games was Alan Wells of Great Britain and this was back in the 1980 Olympic Games. The uptake of runners in sprinting events may have happened sooner with athletes from countries like the USA and Jamaica having the opportunity to compete on a world stage. Runners of West African decent would have been brought across the Atlantic Ocean to these countries during the slave trade through the 16th to the 19th century. The only way to know this for sure is through a detailed study exploring the ethnic origin or all sprinters in the top 25 lists for all records until the present day. This is however outside the scope for this project. With influxes of new competing populations into running events, it is believed that running performances have improved over time, but can the trends relating to the introduction of new completing populations be seen and effects gauged?

6.5 Results: Running performance

6.5.(a) Running performance raw data events

Shown in Figure 6.5 is the mean of the top 25 running raw performance times against historical year from 1948 for men's running events of 800 m and less.

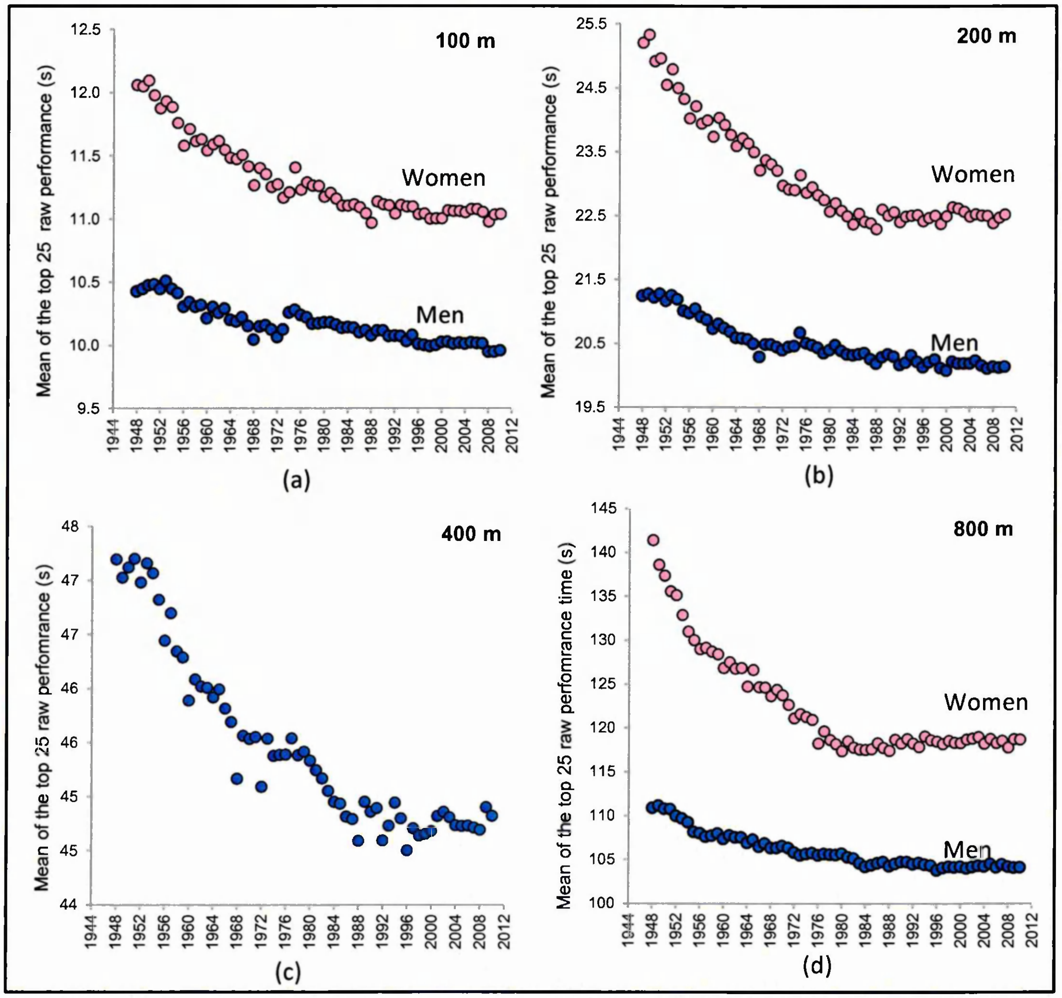


Figure 6.5: Mean of the top 25 raw performance figures in seconds against historical year for the men's and women's running events ≤800 m (a) 100 m, (b) 200 m, (c) 400 m, and (d) 800 m

Now shown in Figure 6.6 is the mean of the top 25 raw performance times against year from 1948 for men's events 1500 m and above.

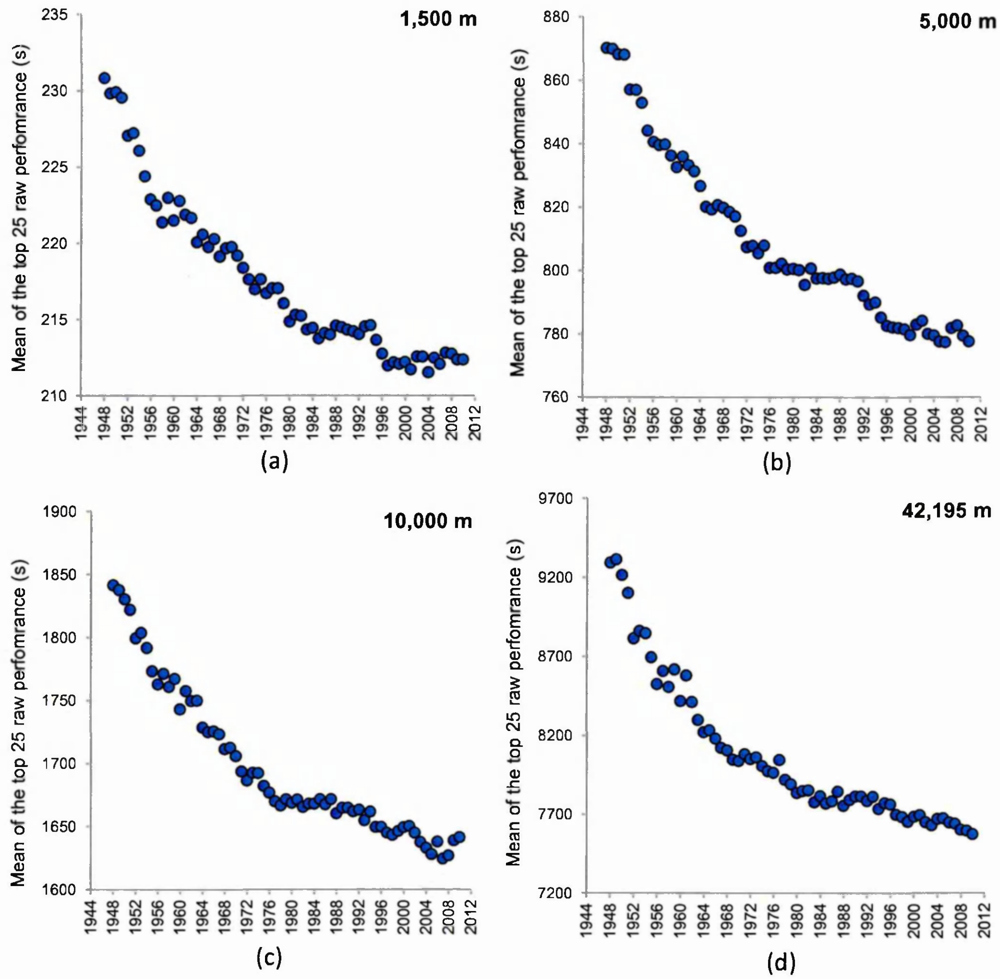


Figure 6.6: Mean of the top 25 raw performance figures in seconds against historical year for the men's running events >800 m, (a) 1,500 m, (b) 5,000 m, (c)10,000 m and (d) The marathon (42195 m)

6.5.(b) Running performance: Average speed data men and women's events

Running performance figures have now been converted in to the average speed to complete each different running event and shown in Figure 6.7. Converting the running performance in to average speed allows all running performance data for the different events to be plotted on the same graph, average speed is a more tangible measure of human performance and are linearly related to other human attributes such as the uptake of oxygen. As expected the shorter running event, the faster the average speed of the running race.

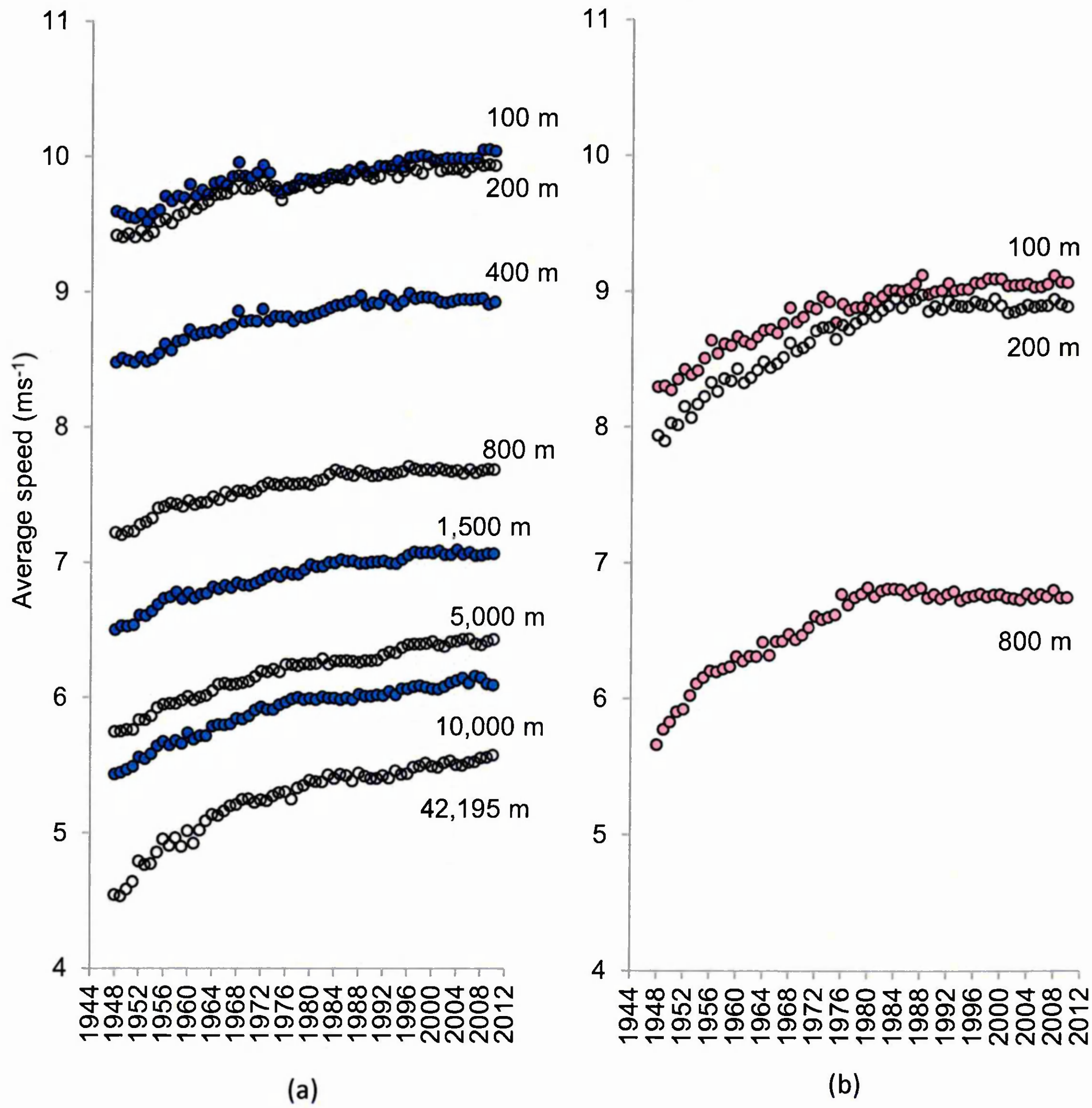


Figure 6.7: Mean of the top 25 performance for each running events represented as average running speed against year for (a) men and (b) women

6.5.(c) Running performance: Performance improvement index (1948 baseline)

The running performance raw data has now be converted in performance improvement indices using a base line of 1948 for the various events, shown below in Figure 6.8 and Figure 6.9 are the performance indices for the men's and women's running events respectively. Follow this in Figure 6.10 are the maximum performance improvement figures for each event shown with the year that this index value is achieved for the various events.

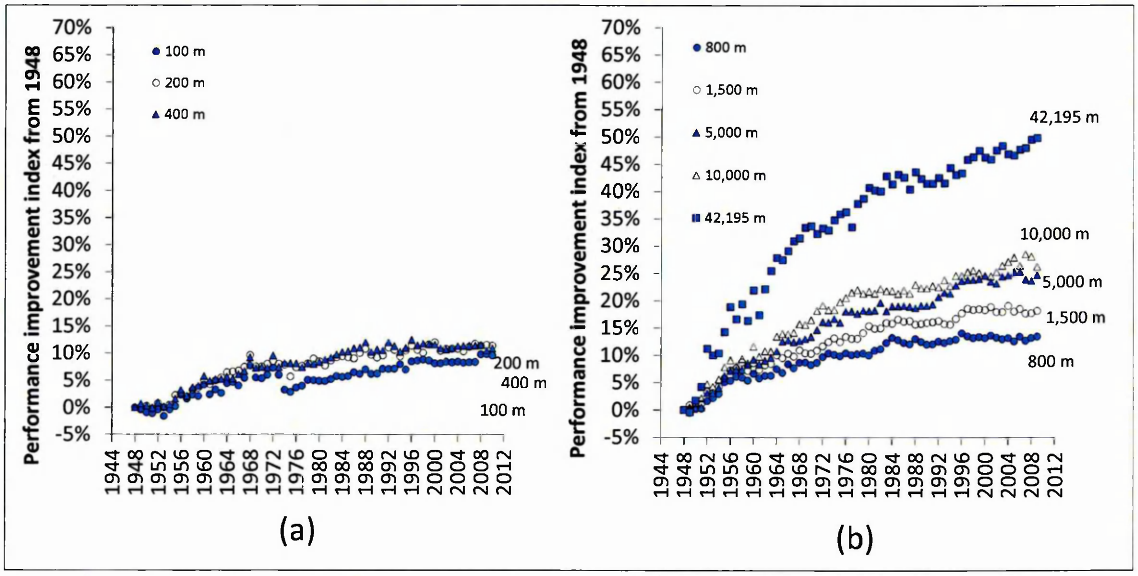


Figure 6.8: Percentage increase in performance improvement index with a baseline of 1948 against year for men's: (a) Running events ≤400 m; (b) Running events >400 m

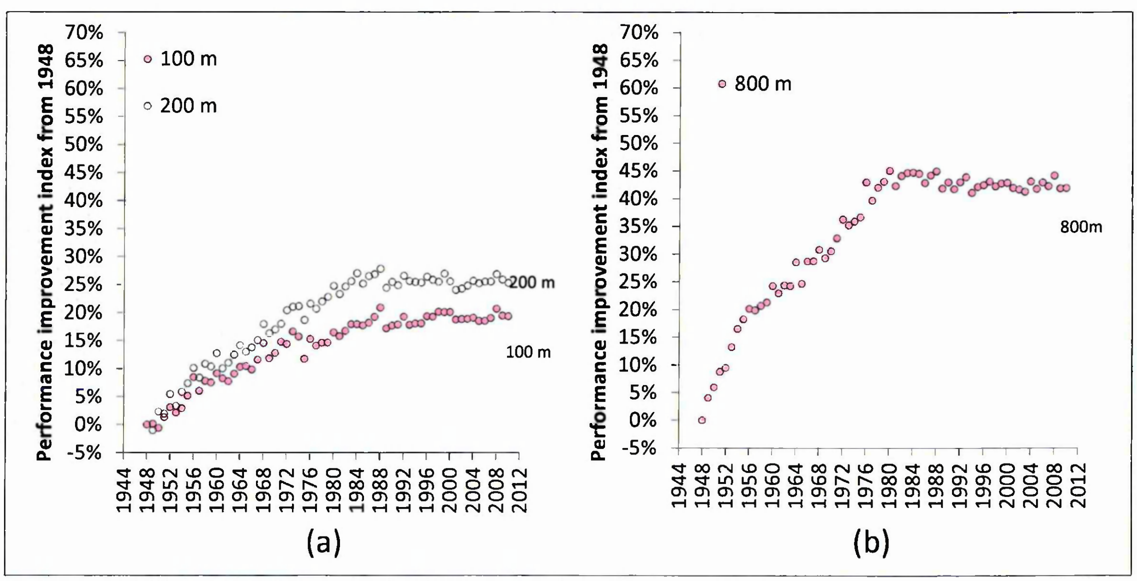


Figure 6.9: Percentage increase in performance improvement index with a baseline of 1948 against year for women's running events: (a) ≤400 m; (b) >400 m

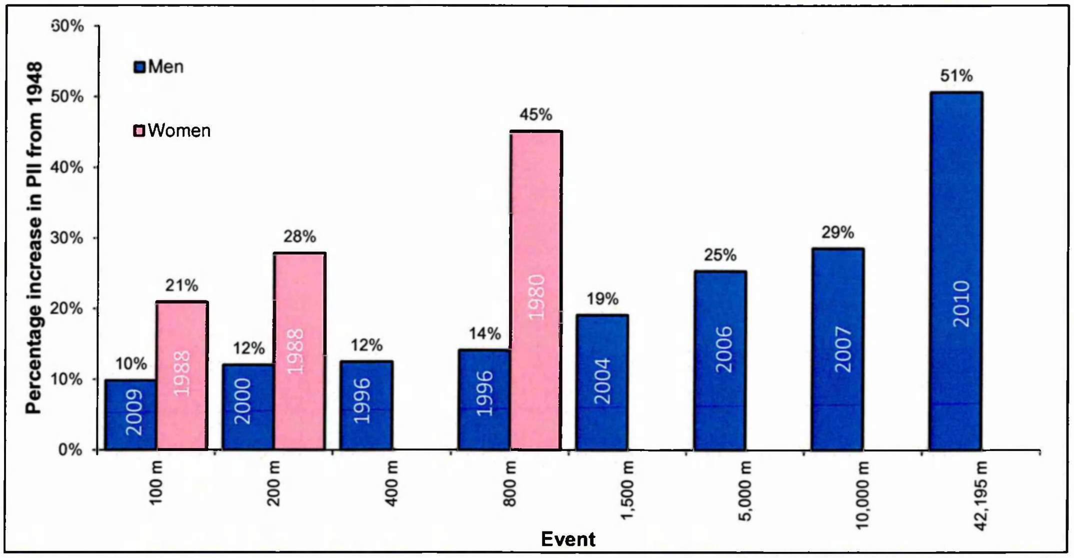


Figure 6.10: Maximum percentage increase in the performance improvement index from 1948 for all running events, shown with year of peak performance.

6.6 Discussion: Running performance

6.6.(a) General trends

Running performance in both men's and women's events have been charted and shown in different formats from Figure 6.5 to Figure 6.9. The first point to notice when examining these figures is that all events examined show a similar general trend of improvement. The general improvement trend in athletic performance from 1948 takes the form of an exponential decay function with a high rate of improvement at the start of the period followed by a reduction in the rate of improvement as time goes by. The asymptotic nature of exponential trends implies that performance in these running events have a theoretical limit, which directly relates to a human physiological limit of performance. It is therefore assumed that the general improvement trends seen within the data can be modelled though the use of exponential functions

6.6.(b) Greater improvement in some events but not others

The maximum percentage increase in the performance improvement index within the different running events are shown in Figure 6.10. A wide range of improvement values are seen, but assuming that all running performances have evolved in the same fashion it is important to explain the differences in improvement between the events examined and there could be two reasons for why this is the case.

Firstly the most obvious answer is that performance across the different running events has improved in a different manner and the improvements seen in the marathon cannot be directly compared to the 100 m sprint. However the performance improvement index attempts to alleviate the differences across the different events. The second possible reason for the differences in performance improvement could be that the base line performance year selected to be 1948, may not represent comparable performance levels in the wide spectrum of running events. For example in the 1948 marathon event was considerably younger than other running events such as the 100 m, with the official marathon distance only being set 27 years earlier in 1921. This could mean the baseline performance for the marathon in 1948 is comparatively poorer than the 100 m or other well established events.

To examine whether this is the case a competitive 1948 men's marathon figure can be estimated using various performance predicting methods (Barder 2011). These methods estimate performance in a wide range of running events based upon a performance from a single event. The predictive methods work well with similar types of running events, for example long distance running events. Therefore a competitive men's 1948 marathon performance figure can be estimated using the actual 1948 10,000 m performance figure. In 1948 it is believed that the 10,000 m was a more established and competitive event with a greater number of competitors competing with more established training regimes. Whereas the marathon in 1948 had fewer competitors and a less advanced training and nutritional knowledge base meaning it was a less developed and competitive event.

Figure 6.11 shows how the percentage difference in performance between the actual marathon time and the predicted marathon time based upon 10,000 m performance various over time. In 1948 we see that the actual marathon performance figure is below par (≈ -20 %). This implies that all the marathon performance improvement index values are offset to higher than expected values due to a lower than expected baseline performance figure. It is not until the 1960s where the actual marathon performance is within 5 % of the predicted marathon performance. From this one can conclude that it was only in the 1960s where the marathon's level of competitiveness was comparable to the 10,000 m.

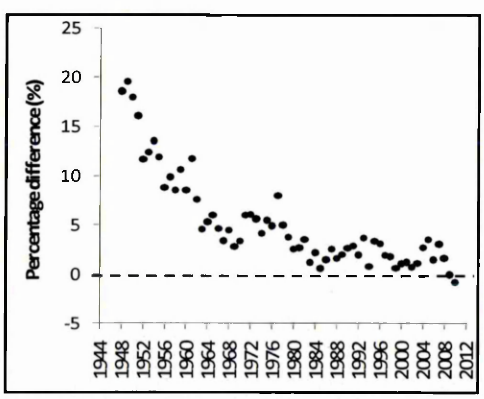


Figure 6.11: Performance improvement index difference between predicted marathon time and predicted marathon time based on actual 10,000 m performances

6.6.(c) Men versus women

Figure 6.10 which represents the maximum attained performance improvement index also illustrates when compared to men, women undergo increased levels of performance improvement in comparable running events. For example the 100 m men's running event underwent a maximum 10 % increase in performance whereas the women's event saw double the maximum improvement at 21 %. The discrepancies between the improvements seen in men's and women's running events of comparable distances could also be due to the choice of baseline performance figures. In 1948 females were conceivably less advanced in the sport than their men's counterparts at that particular time.

One prime reason for this is that all women's running events commenced later than men's events. This would have meant that in 1948 knowledge of women's training regimes, race preparation stages as well as the available competing population were below the levels seen in the more established men's events at that particular time.

6.6.(d) The effect of distance on running performance

Within running events an interesting trend is apparent: the longer the event distance the greater the improvement. Values shown in figure 7 indicate that according to the index the men's 100 m improves 10% and the marathon improves by 51%. As explained earlier, much of the difference in performance could be down to the competitiveness of each different event at the baseline year of 1948. In addition to the levels of competiveness, some of the differences in performance can be explained by an assumption within the performance improvement index calculation. The current index calculation for running assumes that the frontal area of the various athletes is constant and does not vary historically. However, it is evident that sprinters have got bigger and stronger since 1948 meaning their frontal areas have also increased which would increase performance improvement indices seen in sprinting events.

6.6.(e) Accounting for discrepancies in performance improvements

The frontal areas of running athletes can only be precisely gauged though the use of accurate anthropometric data collected from each elite athlete from 1948 up until the present day, however this this data is not readily available. Nonetheless, the frontal area of any athlete can be reasonably estimated by two simple anatomical measures, the athlete's height and mass. It was found that the height and mass of the male athletes within the top 25 are available through various online sources (Mallon et al. 2011). Height and mass data were collected for all male athletes within the top 25 lists from 1948 and a mean value calculated each year. It was found that male runners in sprinting events are getting taller and heavier meaning their frontal area has increased. In the marathon event athletes are more or less the same height and mass now as they were in 1948, however there was an increasing in both height and mass up until the 1980s and prior to the 1980s there was a decreasing trend. This data is shown in Figure 6.12: a and b for the 100 m male athletes and Figure 6.13: a and b for the male marathon event.

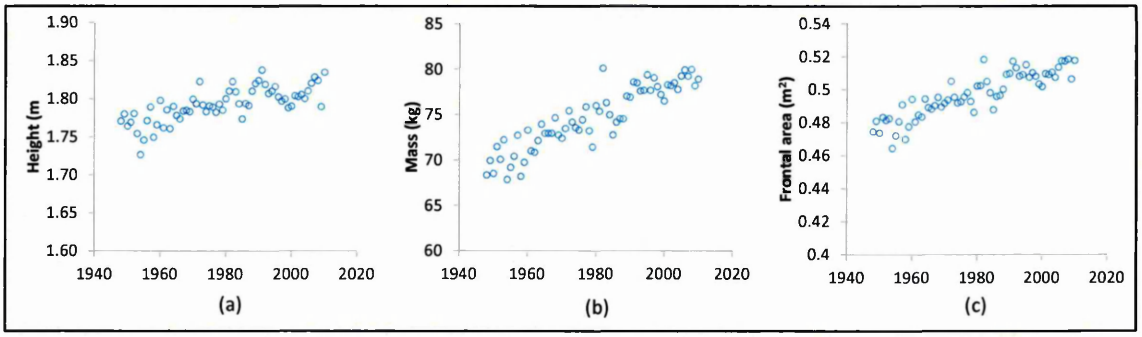


Figure 6.12: Mean frontal area data collected against year from 1948 for the 25 athletes in the 100 m: (A) Athlete height; (B) Athlete mass and (C) Athlete frontal area

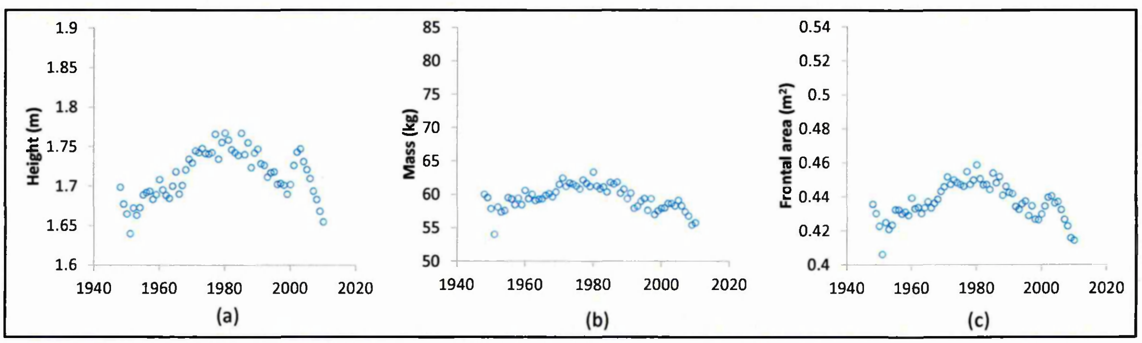


Figure 6.13:Mean frontal area data collected against year from 1948 for the 25 athletes in the marathon: (A) Athlete height; (B) Athlete mass and (C) Athlete frontal area

The height and mass of an athlete can be used to predict the frontal area using a modified Du Bois equation (Du Bois 1916) for estimating the surface area of a human from their height and mass. This equation was quoted by Vaughan and Matravers (1977) is shown the in equation:

$$A_1 = 0.217\, h^{0.725} m^{0.425}, \tag{44}$$

where A_1 is the surface area in m^2, h is the height in metres and mass in the mass in kg. The frontal area of a sprinter may be assumed to be directly proportional to the body surface area arising to the following equation to estimate frontal area A,

$$A = K\,A_1. \tag{45}$$

K is a constant term and found by applying this equation to existing anthropometric data for athletes of known frontal area, height and mass. This method was carried out by Dapena and Feltner (1987) to estimate the frontal area of runners and within this study K was found to be equal 0.24.

Accounting for an athlete's varying frontal area the performance improvement index for aerodynamic events (equation 21), can be modified to:

$$PII = \frac{E_0}{E} = \left(\frac{A_0}{A}\right) \cdot \left(\frac{t}{t_0}\right)^2, \tag{46}$$

where A is the baseline reference frontal area and A_0 is comparison front area of the athlete with the comparison performance.

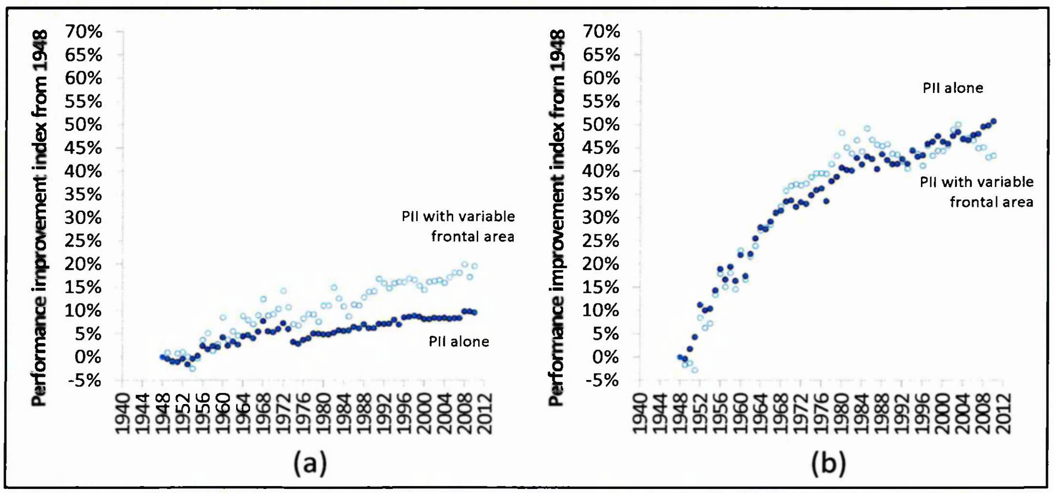


Figure 6.14: Percentage improvement against year with and without consideration for frontal area changes for: (A) the 100 m male athletes and (B) marathon male athletes.

Figure 6.14 shows the new aerodynamic performance improvement index for running accounting for a changing athlete frontal area overlaid with the standard PII. It seems when considering frontal area changes the values of PII for the 100 m are generally higher, whereas the marathon values are not affected. An independent t-test was carried out to see whether accounting for a change in frontal area significantly influenced the means value of performance index. It was found that by accounting for frontal area in the 100 metres, the performance index was greater (M = 1.103, SD = 0.060) than when not accounting for frontal area (M = 1.052, SD = 0.030), t(124) = -6.05, p=0.000000031. As the P value is lower than 0.05, the means are significantly different at the 5% level. However in the marathon, accounting for frontal area showed no significant difference in performance index. With frontal area, the performance index (M = 1.341, SD = 0.150) and when not accounting for frontal area (M = 1.337, SD = 0.139), $t(124) = -0.192$, $p=0.85$. The p value is greater than 0.05 so there is no significance difference in the means of the two data sets at the 5% level.

It is apparent that accounting for frontal area increases the performance index for the 100 metres but not the marathon. The true significance of accounting for frontal area in calculated performance indices for all events needs to be investigated. However, for the purposes of this study the inclusion of frontal area in performance index calculations was not considered. This is because the collection of vast amounts of anthropometric data was unrealistic and unlikely to be complete for all sprinting events and further investigation is warranted. The consequence of not considering frontal area and using an unchanged performance improvement index is discussed in the final chapter under the limitation section.

The marathon and the 100 m have vastly different improvement figures but by considering the level of competiveness at the base level year of 1948 could account for discrepancies. Considering a 20 % lower level of competiveness in the marathon in 1948 over the 10,000 m year, the maximum marathon PII is reduced from 50% to approximately 30%, moving it more in line to the maximum performance improvement seen in the 100 m.

Considering the step change in performance due to the introduction of fully automatic timing in the mid-1970s will increase maximum performance in the 100 m by 5 % to approximately 25 %, bringing the maximum performance figures in both these events to comparable levels.

6.6.(f) Intervention - Fully automatic timing

Within the general improvement trends seen in the 100 and 200 m, a single major step change is apparent. This step change is a consequence of a universal rule change and combined with a technology introduction. This step change correlates to the rule change made by the IAAF in 1976 to make fully automatic timing compulsory for all major championships in running events. The introduction of fully automatic timing has given the impression that running performances in the 100 and the 200 m have decreased. Assuming running performances evolve naturally over time and conform to an exponential decay trend, this apparent drop in performance must be due to the introduction of fully automatic timing.

6.6.(g) Intervention - The drugs effect

Examining Figure 6.11 a large variation can be seen in the years at which peak performances were produced. The earliest year in which a peak performance occurred was in the women's 800 m, in 1980. The other two women's running events examined also had peak performance values produced in the 1980s, with both the 100 and 200 m peaking in 1988. The average to the nearest year in which the performance peaked for women's running events was 1985. This is not the same for men's running events as all have currently peaked within the last 14 years of the present data set, with the average being 2004.

This raises the question: are all the women's athletes from nearly three decades ago better than athletes in the same events today? This is at odds with the assumption of continual human improvement. As mentioned earlier, there must have been an external influencing factor which has improved athletic performance in the 1980s which does not exist today. One possible answer is the use of performance-enhancing drugs, commencing around the 1960s. Today it is widely accepted that the use of performance-enhancing drugs was widespread from the 1960s up until the early 1990s (Donald, 2008; Franke & Berendonk, 1997; Wilson & Derse 2001). Berthelot et al. 2010 also observed a peak in athletic performances in the late 1980 and similarly attributed this to performance-enhancing drugs. What mitigated the widespread use of drugs was the introduction of better drug testing regimes in the late 1980s and early 1990s and later on the creation of the World Anti-Doping Agency (WADA) in 1999.

It appears that some men's events peak more recently which could mean that performance-enhancing drug use may not be as influential in these events. Men's running events have continued to naturally improve and this is likely to be due to a growing male competing population. Influxes of East African runners in long distance running events and West African runners in sprinting events have continued to increase the performance in these events. In addition to this, male running performance may have continued to improve due to better training methods, better medical knowledge or also better nutritional knowledge

The reason that performance-enhancing drugs are more beneficial to female athletes is possibly because of the difference in physiology between male and female athletes. Females in general have more body fat when compared to males of the same height and mass. This increased body fat is the predominant reason why female athletes cannot achieve the same performances levels in comparable running events to male athletes (Stefani 2006). Performance-enhancing drugs like testosterone and anabolic steroids artificially enable female athletes to lose body fat and gain useful muscle mass which benefits running performance. Male athletes may not benefit as much from these performance-enhancing drugs as through modern training regimes and diet the percentage of body fat for males can be lowered by these means. Males also naturally produce higher levels of testosterone when compared to females which aids in producing lean muscle mass (Brodsky et al. 1996). There is a lot of evidence suggesting that performance-enhancing drugs were also widely used by male athletes and the high profile case of Ben Johnson who was stripped of his Gold medal in the 1988 Olympic Games after testing positive for performance-enhancing drugs illustrates this. Nevertheless there is no noticeable effect on men's running performances caused by performance-enhancing drug use or newly implemented testing procedures

Looking at performance-enhancing drugs use in men's running events from a different point of view could mean that performance-enhancing drugs are still widely used by male athletes and that the interventions to stop the widespread use of drugs has only influenced the women's events. However this seems unlikely with the extensive drug testing programs currently being undertaken throughout the world to stop athletes from taking performance-enhancing drugs.

6.7 Interventions that will be modelled: Predicted interventions

After examining running performance data for different events is has become apparent that there are visible trends that can be attributed to historical interventions. These visible trends will be attempted to be modelled using the methods explained in methods part II "Modelling performance data" and implemented in methods part III "Application of performance models".

6.7.(a) Fully automatic timing systems introduction

It is apparent there is a major step change in the sprinting events of 400 m and lower in distance. This is in line with the year that fully automatic timing was made compulsory in 1976, with a step change seen in 1975 where all performances in the top 25 were recorded using fully automatic timing. A step change was decided to be implemented in 1975 within sprinting events.

As fully automatic timed sprinting races show an apparent drop in performance in running these results need to be isolated from the original hand timed performances. In the years 1973 and 1974 it became apparent that these years contain performances quoted to a single decimal place or to two decimal places, the former indicative of hand timing and the latter indicative or fully automatic timing. As a result of this discovery it was decided to omit running performance data for years which contained a mix of hand timing and fully automatic timing performance results from the following analysis.

6.7.(b) The Usain Bolt effect - Step change in 2008.

Within the 100 m sprint race it became apparent that there was a step large step change in 2008. The reasoning behind this step change is not known but this was the year Usain Bolt set a new World Record time of 9.69 seconds. It seems that the whole elite field within the top twenty five saw a step increase in performance. The reason behind this could be because it was an Olympic year in combination with the rise of Usain Bolt. A step change in 2008 was applied to the 100 m and 200 m men's events as Usain Bolt competed in both events. This step change will be called the Usain Bolt effect will be discussed later.

6.7.(c) Performance-enhancing drugs

Performance-enhancing drugs have evidently affected athletic sports and one possible way of gauging their influence is by ascertaining the magnitude of the effect of the introduction of new drug testing procedures which mitigate and presumably stops the use of performance-enhancing drugs at least for a short period of time. There are two ways this could be done, firstly the introduction of new drug testing procedures technologies will instantaneously stop performance-enhancing drug use in athletic sports and can be modelled with a step change. Or secondly drug testing technologies and procedures may take time to be adopted and athletic performance may fall over a period of time as the drug testing technologies are adopted. This second uptake of drug testing technologies can be modelled with a linear decline model (MODEL 3.2).

The adoption of performance-enhancing drug use may also take the form of a technology uptake curve, were drugs are taken up over a period of time so that performances slowly increase up until a certain point. Drug uptake can be modelled using a linear technology uptake model (MODEL 3.1). The improvement function will attempt to implement four different steps to account for the use of performance-enhancing-drug use in running performance, the selected years for their implementation are now going to be explained.

6.7.c.(i) Drug testing step changes 1989 and 2000

Firstly a step change will be implemented in 1989 to account for the introduction of compulsory random drug testing procedures. Next another step change will be implemented in 2000, accounting for the formation of the World anti-doping agency

(WADA) in 1999 and the centralization of drug testing procedures and drug testing technology knowledge.

6.7.c.(ii) Linear uptake and declines

The adoption of the use of performance-enhancing drugs by athletes may take the form of a linear technology uptake, however the dates of this are difficult to ascertain and the full scale of performance-enhancing drug use is difficult to fully quantify. This is because performance-enhancing drug use is prohibited in modern athletic events and their use is secretive. With recent evidence being found of systematic doping in East Germany we can conclude that performance-enhancing drug use was most definitely being undertaken by at least one nation (Wilson & Derse 2001).

From historical evidence it is believed that the use of performance-enhancing drugs started in the 1960s but only used by a minority of athletes in specific sports. The knowledge of performance-enhancing drugs on performance levels as well as side effects was still in its infancy and it was not until the end of the 1960s where the use of performance-enhancing drugs was established in the athletic community.

Throughout the 1980s it is believed that performance-enhancing drug use became widespread and peaked in 1988, culminating at the Seoul 1988 Olympic Games. The furthering of performance-enhancing drug use was possibly halted with introduction of random drug testing from 1989 onwards. For the purposes of the linear uptake model for drug uptake, a start year of 1968 was chosen with an end year of 1988, in addition to a step change in 1989 due to random drug testing implementation.

Another possibility is that the implementation of these drug testing procedures did not instantaneously stop the use of performance-enhancing drugs use in sport and throughout the 1990s drug use declined. This can be modelled with a linear uptake and decline function with the linear uptake starting in 1975, ending 1988 and the decline starting in 1988 and ending in 1999 with the addition of a step change in 2000 due to the formation of WADA. A summary of the models used to account for performance drug use in running is shown below in Table 6.1.

Table 6.1: Summary of the models used to account for the effects of performance-enhancing drug use on athletic performance

	Intervention to be modelled	**Model description**
1	Introduction of random drug testing 1989	Step change 1989
2	Formation of WADA 1999	Step change 2000
3	Uptake of performance-enhancing drugs and improvements in drug testing procedures	Linear uptake 1968-1988 Step change in 1989

4	Uptake of performance-enhancing drugs and uptake of drug testing procedures to mitigate the use of performance-enhancing drugs	Linear uptake 1968 – 1988 Linear decline 1988 – 1999 Step change in 2000

6.7.(d) Population influx

The numbers of runners representing African countries in the top twenty five lists for the various running events examined have evidently increased from around the 1980s and this is shown in Figure 6.1. This uptake can be modelled through the use of a linear uptake model with a similar theory behind the adoption of technology. It has become apparent that in the men's 800 m and 1500 m events saturation does not occur, where by all runners in the top 25 lists represent African countries. Instead around the year 2000 the numbers of runners representing African runners in the top twenty five lists seems to have levelled out at about 15. For these events it was decided that the linear population influx model should start in 1980 and end in 2000. There could be many reasons why runners represent African countries have not saturated the entirety of the top lists in the 800 m and the 1500 m events, for example these events are more tactical and that any advantage that may come by having an African decent is not as pronounced. It may also be apparent that 800 m and 1500 m events are not as prestigious as the long distance events within these competing African nations. This could mean that there are fewer runners from each African country as there might not be the investment or elite athlete numbers (as they have turned to longer distance events) as emphasis in these countries is placed on the longer distance running events.

Nevertheless it is apparent that the longer distance running events the men's 5,000 m, 10,000 m and the marathon are saturated with runners from African countries, which indicates that runners of East African descent possess an advantage over other runners. The year at which saturation of African runners occurs has been shown in Table 6.2. These years are the end years of the linear uptake model used to model the influx of the new population.

The only women's event to be modelled with a linear population influx model is the 800 m. There seems to be a population influx commencing later in 1988 but this influx is not as pronounced as in the men's events. Saturation also does not occur in this women's event but seems to be increasing right up until the present data set, possibly indicating that the influx of runners representing African countries has been delayed in comparison to the men's events and will continue after the present data set. The reasons for a delay in the uptake of runners from African countries could be because there is not a much emphasis on women's athletics in these African nations as there is on men's running events. It could be possible that it is only within the last 10 to 15 years where women runners from African countries have really started to compete at a high international standard and feature in the top twenty performance lists. The number of women runners representing African countries is likely to increase over the coming years and this is likely to be accompanied with an increase in performance. A summary of the linear uptake start and end years implemented during the improvement function generation process are shown in Table 6.2.

Table 6.2: Uptake and saturation of runners representing African countries in the different running events: start and end years for linear uptake model

Event	Uptake year	Saturation year
Men's 800 m	1980	2000 (not saturated)
Men's 1,500 m	1980	2000 (not saturated)
Men's 5,000 m	1980	2003
Men's 10,000 m	1980	2007
Men's 42,195 m	1980	2009
Women's 800 m	1988	2010 (not saturated)

6.8 Improvement function generation steps

It was decided to split the improvement function generation routine in to two different categories. The first category is for sprinting events or events of 400 m and less, and the second category is for middle distance and long distance running events of 800 m and above. Two categories were chosen because it became apparent that different interventions arise in the different running events and logically they have been split in to sprinting and middle/long distance categories. The improvement function generating steps are now shown for each category in Table 6.3 for sprinting events of 400 m and below and Table 6.4 for middle and long distance event of 800 m and above. Each proceeding step implements an additional intervention modelling function supplementing the existing improvement function. Initially all the modelling steps were applied to the different running event within each category.

Table 6.3: Improvement function generation steps and description for sprint running events men and women ≤400 m

Step no.	Intervention modelled:	Model description:	IF GUI model no.
1	Global improvement	Global improvement trend	2
2	Fully automatic timing introduction	step change: 1975	3
3	Usain Bolt effect (100 / 200 m)	2 step changes:1975/2008	4

4	Drugs step change 1 1989	2/3 step changes: 1975/(2008)/1989	4 or 5
5	Drug step change 2 2000	3/4 step changes: 1975/(2008)/1989/2000	5 or 87
6	Drugs linear uptake 1968 – 1988 and drug testing 1989 and 2000	Linear uptake:1975-1988 and step change: 1989 Step change: 2000	54 or 88
7	Drugs up and down 1968 – 1988 – 1999 Drug testing 2000	Linear uptake:1975-1988 Linear down:1988-1999 Step change: 2000	*58 or 89*
8	+ Olympics	Periodic function 4 years from 1948	*59 or 90*
9	+World Championships(1983-4 year period/1991-2 year period	Periodic function 4 years from 1983, 2 years from 1991	*91 or 92*

Table 6.4: Improvement function generation steps and description Middle and long distance events men and women >800 m:

Step no.	**Intervention modelled:**	**Model description:**	**IF GUI model no.**
1	Global improvement	Global improvement trend	2
2	Influx of new running population African runners	Linear uptake with specific years shown in table 6.2	41
3	Drugs step change 1 1989	1 step changes:1989	*74*
4	Drug step change 2 2000	2 step changes: 1989/2000	95
5	Drugs linear uptake 1968 – 1988 and drug testing 1989 and 2000	Linear uptake:1975-1988 and step change: 1989 Step change: 2000	77
6	Drugs up and down 1968 – 1988 – 1999 Drug testing 2000	Linear uptake:1975-1988 Linear down:1988-1999 Step change: 2000	98
7	+ Olympics	Periodic function 4 years from 1948	99
8	+World Championships(1983-4 year period/1991-2 year period	Periodic function 4 years from 1983, 2 years from 1991	*100*

6.9 Results – graphical representation and goodness of fit

6.9.(a) Steps for fitting the improvement function to the 100 m men's event

Shown below in Figure 6.15 through to Figure 6.24 are the graphical representations of the improvement function fitting steps for the 100 m men's event (IF analysis for events 400 m and below, including the Usain Bolt effect).

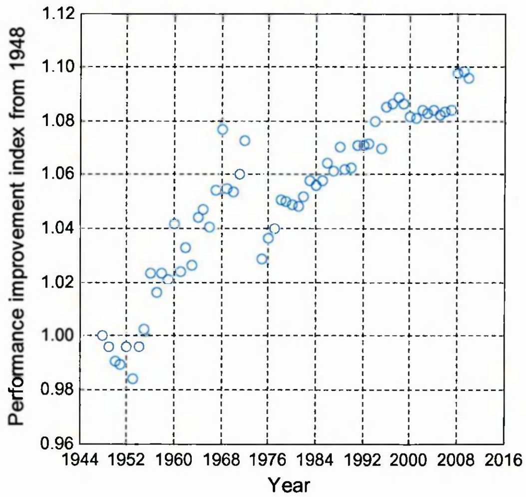


Figure 6.15: Improvement function generator showing performance data against historical year in the 100 m men's event

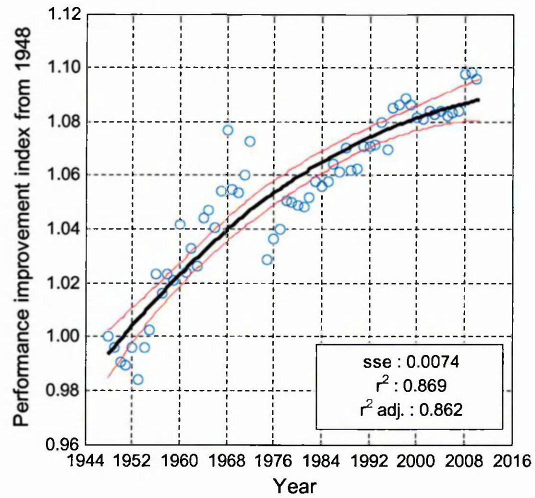


Figure 6.16: Improvement function generator showing performance data against historical year in the 100 m men's event with: (1) standard exponential, global improvement function

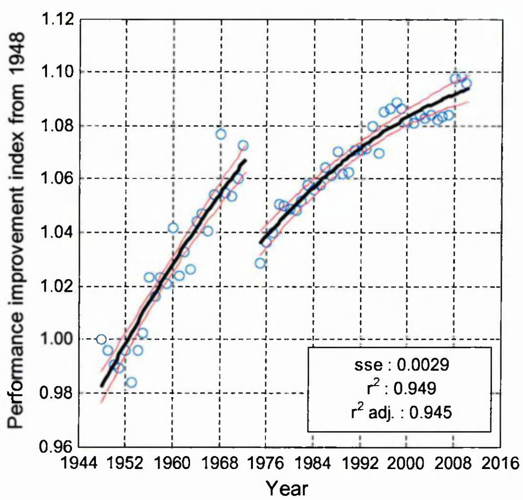


Figure 6.17: Improvement function generator showing performance data against historical year in the 100 m men's event with: (1) standard exponential, global improvement function, (2) step change due to F.A.T. in 1976

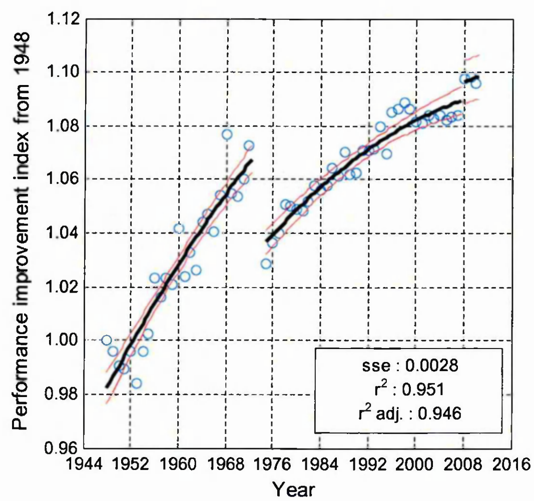


Figure 6.18: Improvement function generator showing performance data against historical year in the 100 m men's event with: (1) standard exponential, global improvement function, (2) step change due to F.A.T. in 1976, (3) step change due to Usain Bolt effect

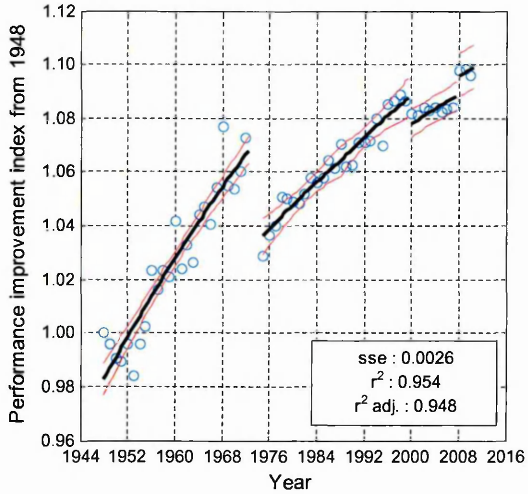


Figure 6.19: Improvement function generator showing performance data against historical year in the 100 m men's event with: (1) standard exponential, global improvement function, (2) step change due to F.A.T. in 1976, (3) step change due to Usain Bolt effect 2008 (4)step change due to introduction of random drug testing 1989

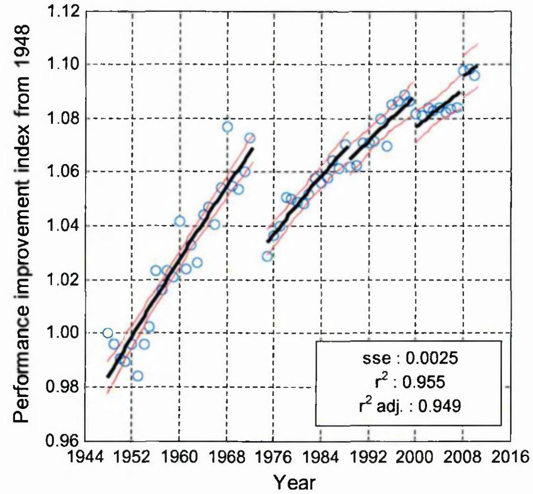


Figure 6.20: Improvement function generator showing performance data against historical year in the 100 m men's event with: (1) standard exponential, global improvement function, (2) step change due to F.A.T. in 1976, (3) step change due to Usain Bolt effect 2008 (4)step change due to introduction of random drug testing 1989 (5) step change due to WADA formation 1999

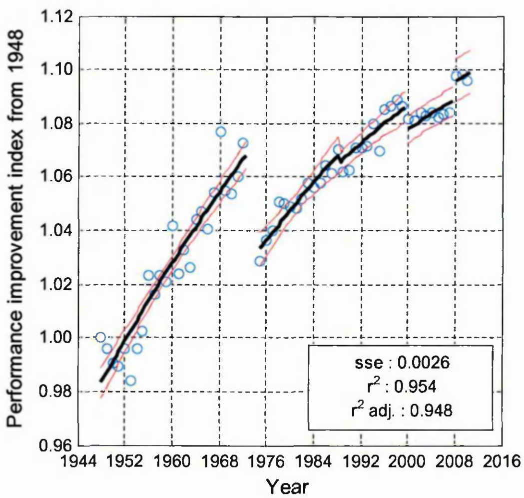


Figure 6.21: Improvement function generator showing performance data against historical year in the 100 m men's event with: (1) standard exponential, global improvement function, (2) step change due to F.A.T. in 1976, (3) step change due to Usain Bolt effect 2008 (4) step change due to WADA formation 1999 (5) Drugs uptake 1968 - 1988

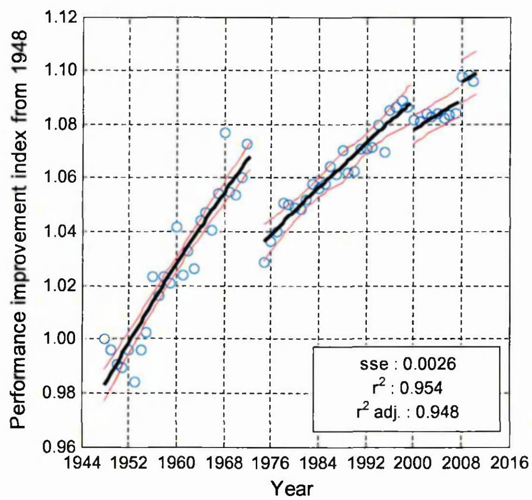


Figure 6.22: Improvement function generator showing performance data against historical year in the 100 m men's event with: (1) standard exponential, global improvement function, (2) step change due to F.A.T. in 1976, (3) step change due to Usain Bolt effect 2008 (4) step change due to WADA formation 1999 (5) Drugs up and down 1968 – 1988 – 1999

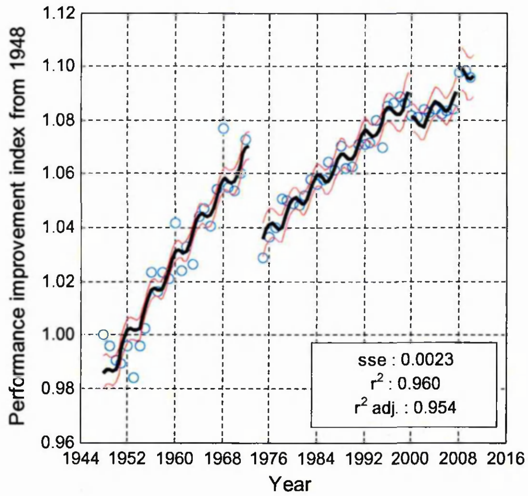


Figure 6.23: Improvement function generator showing performance data against historical year in the 100 m men's event with: (1) standard exponential, global improvement function, (2) step change due to F.A.T. in 1976, (3) step change due to Usain Bolt effect 2008 (4) step change due to WADA formation 1999 (5) Drugs up and down 1968 – 1988 – 1999 (6) Olympics 4 year period

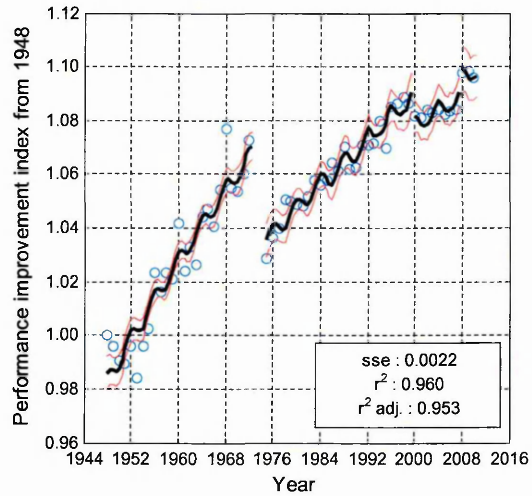
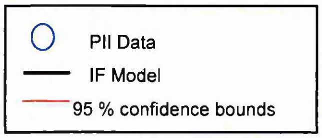


Figure 6.24: Improvement function generator showing performance data against historical year in the 100 m men's event with: (1) standard exponential, global improvement function, (2) step change due to F.A.T. in 1976, (3) step change due to Usain Bolt effect 2008 (4) step change due to WADA formation 1999 (5) Drugs up and down 1968 – 1988 – 1999 (6) Olympics 4 year period (7) World championships from 1983



6.9.(b) Assessing the goodness of fit values – 100 m men's event

The change in the adjusted regression coefficient has been plotted for each step in generating the improvement function and this is shown in Figure 6.25 for the 100 m men's event. The adjusted regression coefficient takes into account the degrees of freedom of the model. An increase in adjusted regression coefficient indicates that the more complex model has a better fit based upon the degrees of freedom of that model. If the adjusted regression coefficient does not increase there are two possible reasons: (1) the more complex model does not account for the intervention in this case or (2) the intervention is not found within the performance data set. If there was no increase in the adjusted regression coefficient, it was assumed that that the more complex modelling step could not be feasibly applied and left out of the final model in that particular event.

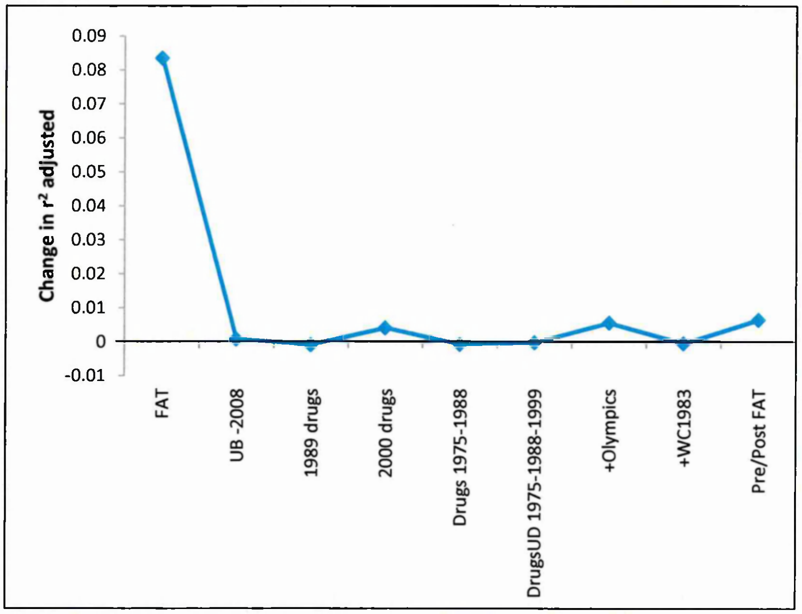


Figure 6.25: Change in adjusted regression coefficient for each step in fitting the improvement function to the men's 100 m running event

Shown in Figure 6.25 is the adjusted regression coefficient at each improvement function modelling step for the 100 m men's event. The adjusted regression coefficient does not increase for the 1989 drug step change, the linear uptake of drugs, linear uptake/decline as well as the world championships effect.

6.9.(c) Quantification of the interventions men's 100 m

For the 100 m men's event the size of the interventions model within the performance improvement trend are shown in Table 6.5. The intervention magnitudes are taken from the most advanced model step which contains that specific intervention function. For example the step change in 1989 for drugs was only used for the improvement function up until fitting step 5, and this is where the 1989 step change value is obtained.

Table 6.5: Performance improvement value and raw time in second for the different intervention modelled for the 100 m men's event

Intervention	PII (%)	+/-	Time (s)	+/-
Global predicted limit	116.6%	3.1%	9.65	0.13
Fully automatic timing	-3.6%	0.8%	0.19	-0.04
Usain Bolt step change 2008	0.7%	0.8%	-0.03	-0.04
Linea population influx	Not modelled			
Drugs step change 1989	Not found to improve fit			
Drugs step change 2000	-1.1%	1.0%	0.06	-0.05
Linear uptake of drugs 1968-1988	Not found to improve fit			
Linear up/down drugs 1968-1988-1999	Not found to improve fit			
Olympics (complete data set)	0.3%	0.2%	0.02	0.01
World Championships (1983 onwards)	Not found to improve fit			

6.10 Goodness of fit value, regression coefficients for all running events and modelling steps – assessing interventions

Shown below in Figure 6.26, Figure 6.27 and Figure 6.28 are the changes in adjusted regression coefficient for each different modelling step applied to the different running events. Where the regression coefficient does not increase with a modelling step, it is believed that the intervention that this modelling step is attempting to gauge is not present and omitted from the final model. Furthermore if any parameters are found which are not irregular, such as a negative gradient for a drugs/population uptake, or a positive effect from a drug testing introduction, this intervention is also believed not be present and left out of the final improvement function. A summary of unexpected parameters values and the models they are associated with are shown in Table 6.6. A final improvement function model was selected based upon the interventions that are believed to be present in each data set as well as taking in to account any irregular modelling parameters. The description of each model for each running event has been summarised in Table 6.7.

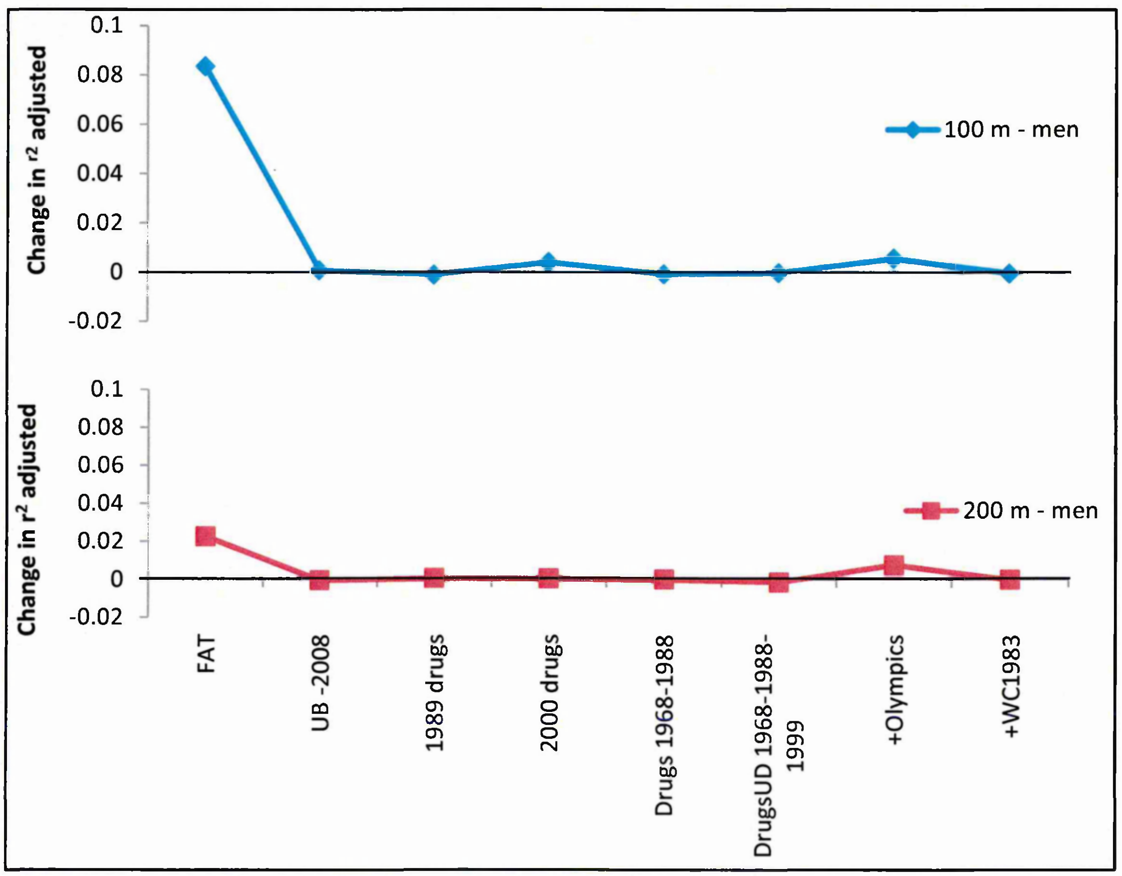


Figure 6.26: Change in adjusted egression coefficient for the modelling steps in the 100 and 200 m men's events

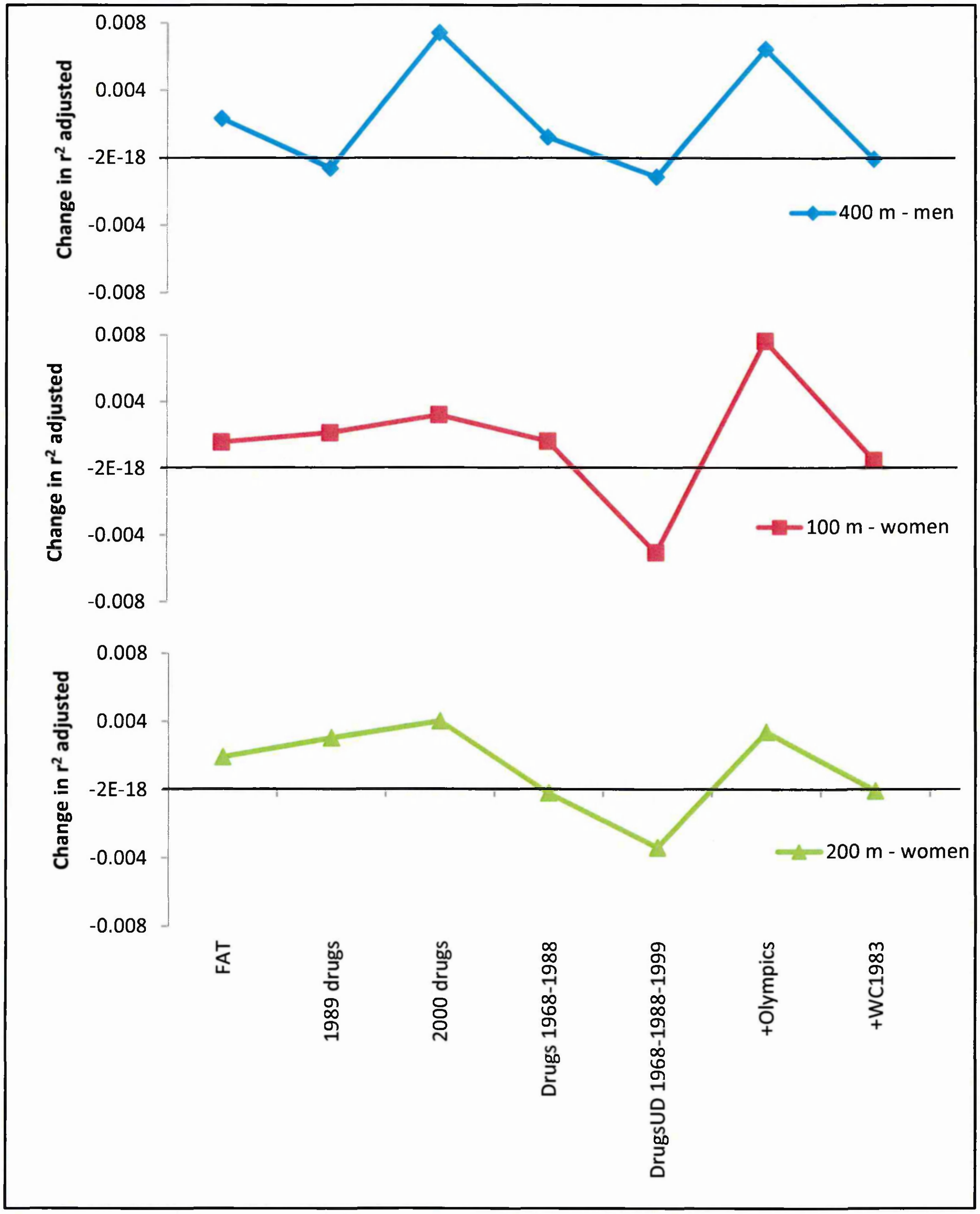


Figure 6.27: Change in adjusted egression coefficient for the modelling steps in the 400 m men's and 100 and 200 m women's events

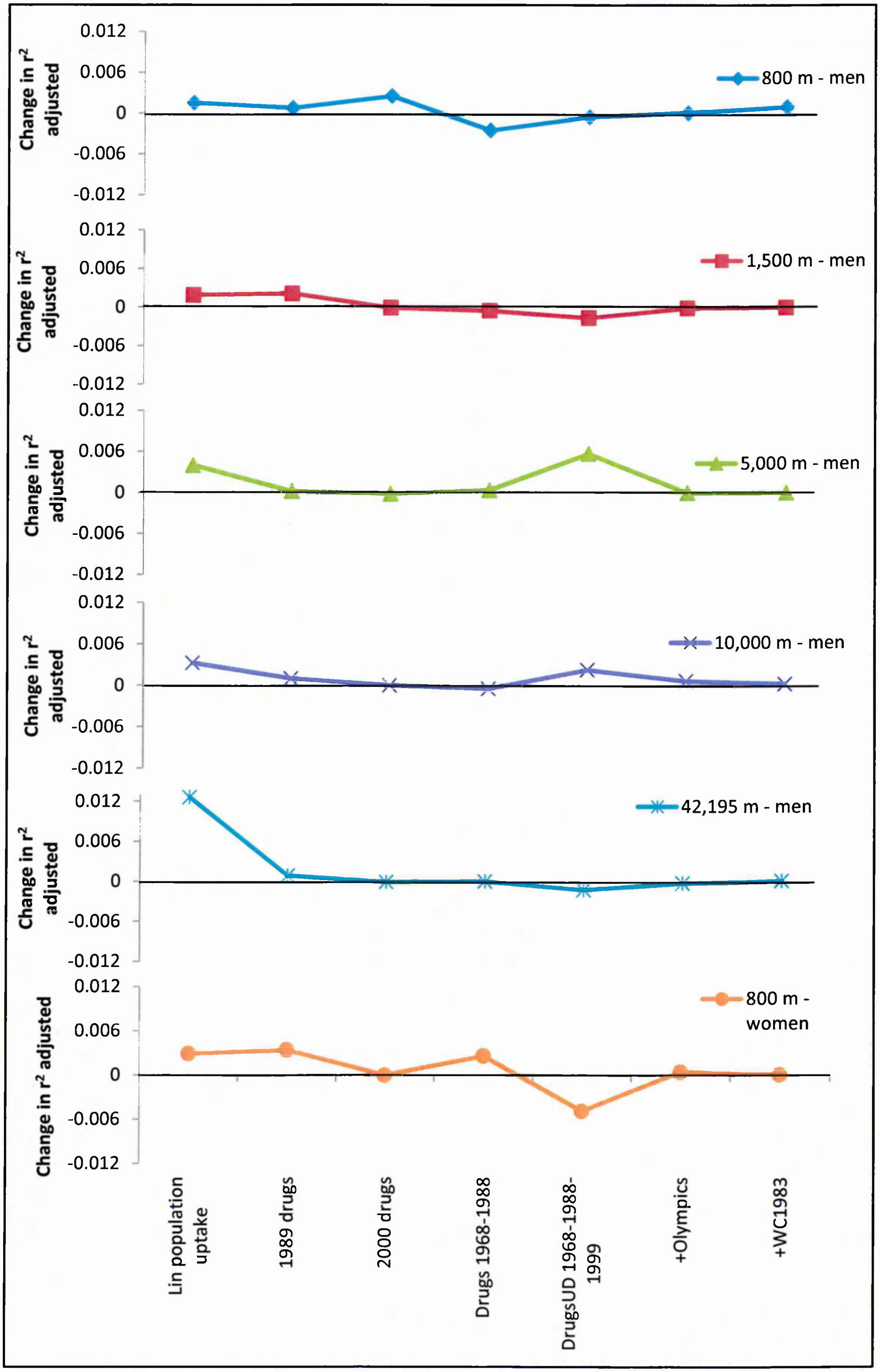


Figure 6.28: Change in adjusted regression coefficient for the modelling steps in the middle and long distance running events for both men and women

Table 6.6: Interventions for the different events that have been excluded from the final improvement function model as unexpected parameters were found

Event	Modelling step/ intervention	Reason for omitting from final model
Men's 1500 m & 10000 m	World Championships	Negative effect found
Men's 10000	Drugs step 2000	Positive effect found
Men's 5000 m	Drugs uptake 1975-1988	Negative effect found
Men's 5000 m and 10000 m	Drugs uptake and decline	Negative uptake/positive decline gradient found

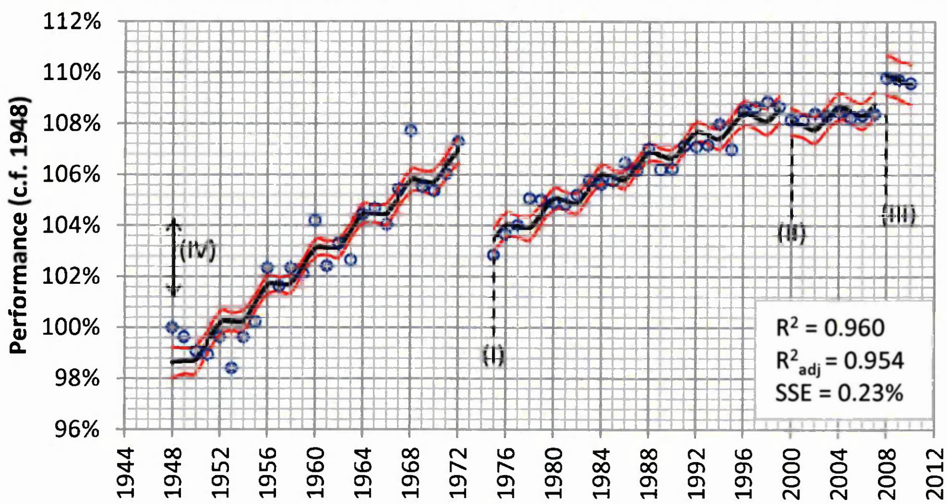
Table 6.7: Final improvement function model and GUI assigned model number, customised for each event

Event	Model description	Model type
100 m - men	FAT + UB + 2000 drugs + Olympics	Exp + 3 steps + Olympics
200 m - men	FAT + 1989 drugs + 2000 drugs + Olympics	Exp + 3 steps + Olympics
400 m - men	FAT + 2000 drugs + lin drugs + Olympics	Exp + 2 step + lin Drugs + Olympics
800 m - men	Lin pop + 1989 + 2000 + Olympics + WC	Exp + lin pop + 1 step + Olympics + WC
1500 m - men	Lin pop + 1989	Exp + lin pop + 1 step
5000 m - men	Lin pop + 1989 + WC	Exp + lin pop + 1 step + WC
10000 m - men	Lin pop + 1989 + Olympics + WC	Exp + lin pop + 1 step + Olympics + WC
42195 m - men	Lin pop + 1989 + lin drugs + WC	Exp + lin pop + lin drugs + WC
100 m - women	FAT + 2000 drugs+ Lin drugs + Olympics+ WC	Exp + 2 steps + Lin drugs + Olympics + WC
200 m - women	FAT + 2000 drugs+ Lin drugs + Olympics+ WC	Exp + 3 steps + Olympics
800 m - women	2000 drugs+ Lin drugs + Olympics+ WC	Exp + 1 steps + Lin drugs + Olympics + WC

6.11 Final improvement models – running

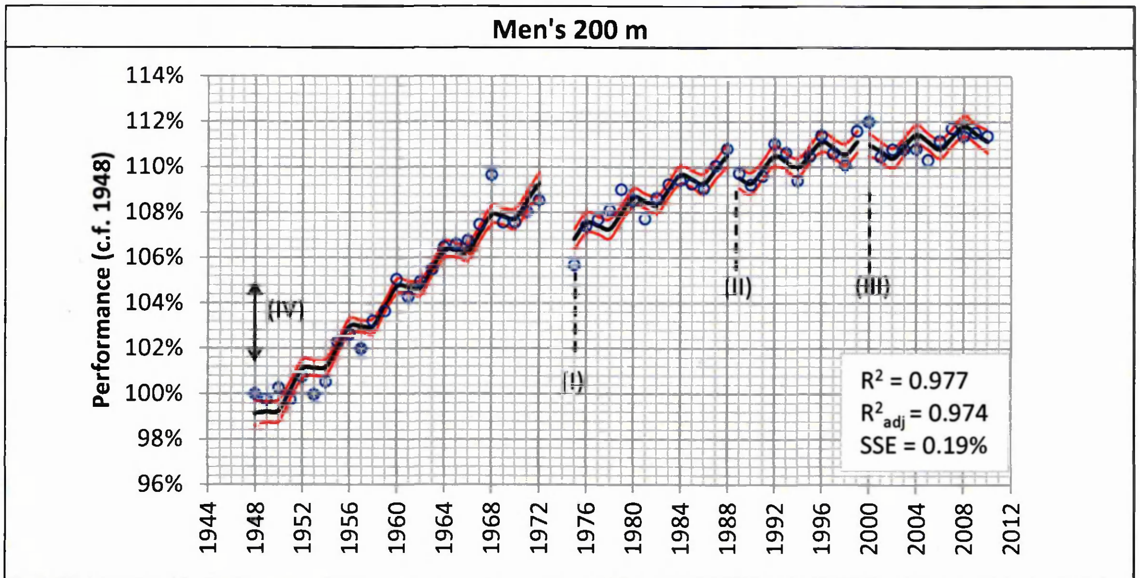
The final improvement functions models for all the running events examined have been represented graphically from Figure 6.29 to Figure 6.39. Each intervention accounted for within the final improvement function has also been labelled and the size of the different parameters summarised.

Men's 100 m



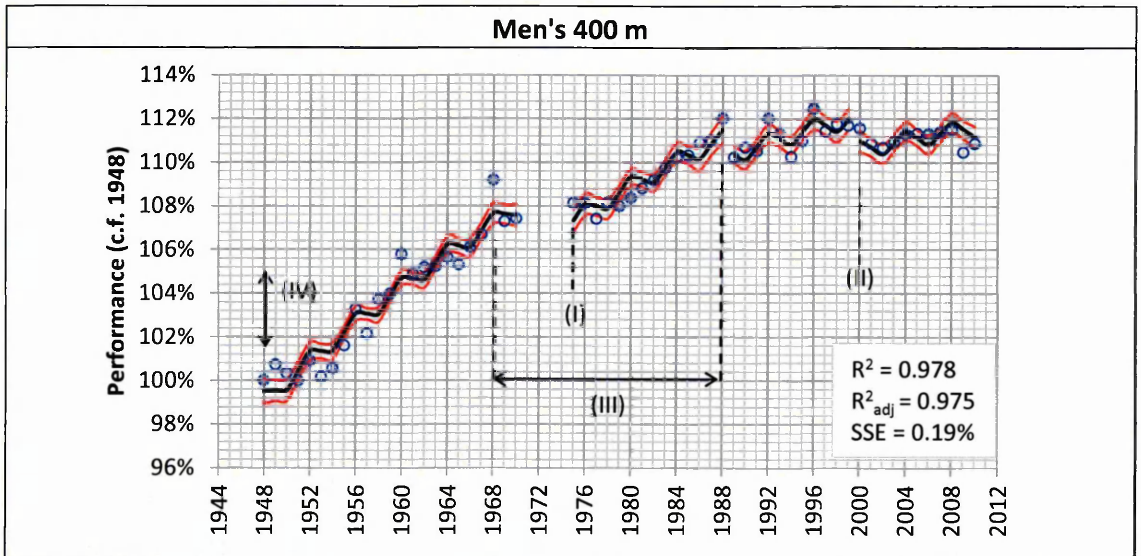
	Intervention	Parameters
	Global improvement	L=117.01% (± 3.52); a=0.2599 (± 0.07); b=3.5232 (± 0.77)
I	Fully automatic timing	k_1=96.20% (± 0.73); k_1year=1975
II	Formation of WADA	k_2=99.12% (± 0.78); k_2year=2000
III	Usain Bolt effect	k_3=100.66% (± 0.85); k_3year=2008
IV	Olympic Games	Amp, A=0.33% (± 0.24)
	Goodness of fit	R^2=0.960; R^2_{adj}=0.954; MSE =0.004%; SSE=0.23%

Figure 6.29: Final improvement function model for the men's 100 m sprint event



	Intervention	Parameters
	Global improvement	L=117.25% (± 3.44); a=0.1564 (± 0.05); b=4.9814 (± 1.23)
I	Fully automatic timing	k_1=97.27% (± 0.72); k_1year=1975
II	Stricter drug testing	k_2=99.29% (± 0.76); k_2year=1989
III	Formation of WADA	k_3=99.40% (± 0.74); k_3year=2000
IV	Olympic Games	Amp, A=0.44% (± 0.22)
	Goodness of fit	R^2=0.977; R^2_{adj}=0.974; MSE =0.003%; SSE=0.19%

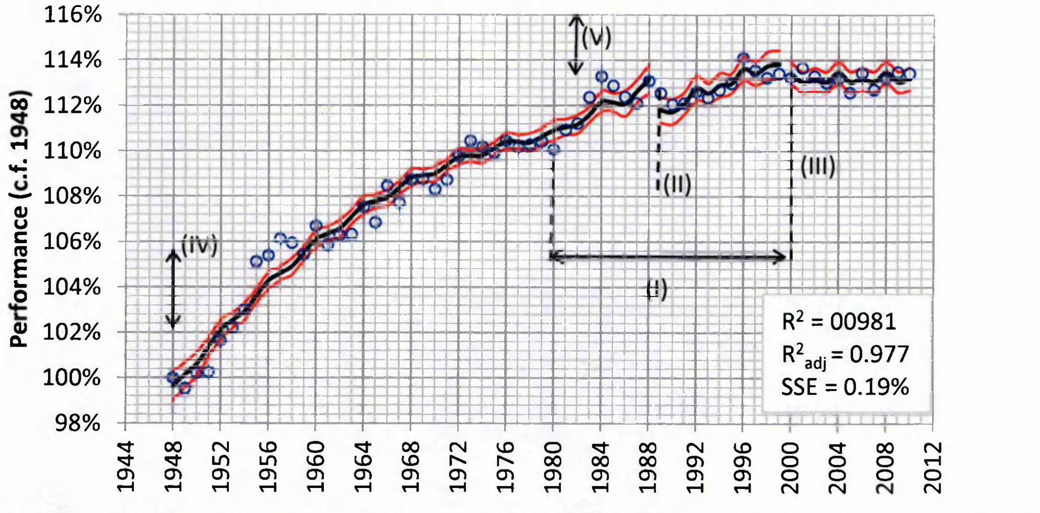
Figure 6.30: Final improvement function model for the men's 200 m sprint event



	Intervention	Parameters
	Global improvement	L=117.00% (± 2.73); a=0.1828 (± 0.05); b=4.5250 (± 0.99)
I	Fully automatic timing	k_1=97.74% (± 0.95); k_1year=1975
II	Formation of WADA	k_2=98.62% (± 0.69); k_2year=2000
III	Uptake of drugs before stricter drug testing	D=0.05%yr^{-1}(± 0.04); D_{peak}=0.97% (± 0.86); D_{start}=1968 ; D_{end}=1988
IV	Olympic Games	Amp, A=0.43% (± 0.23)
	Goodness of fit	R^2=0.978; R^2_{adj}=0.975; MSE =0.004%; SSE=0.19%

Figure 6.31: Final improvement function model for the men's 400 m sprint event

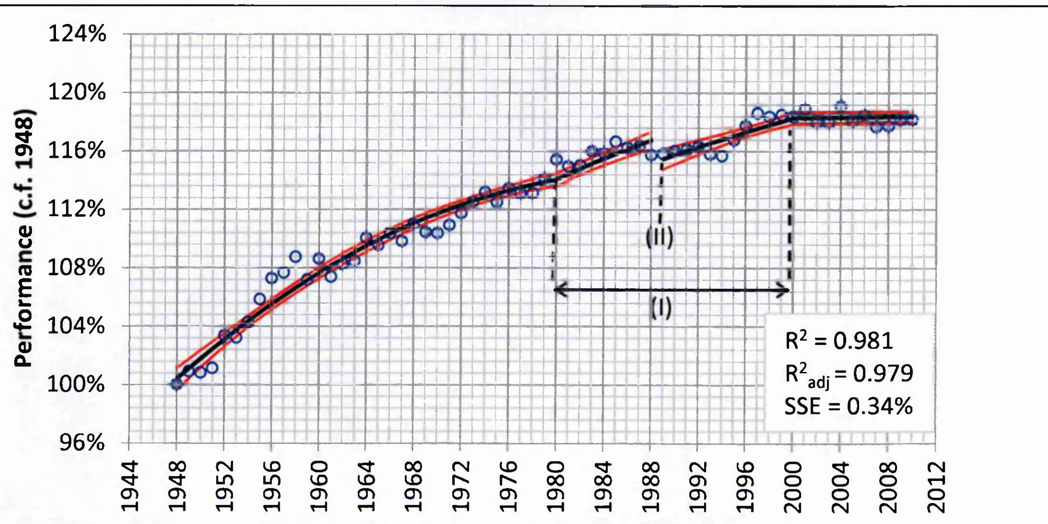
Men's 800 m



	Intervention	Parameters
	Global improvement	L=115.57% (± 0.86); a=0.0466 (± 0.03); b=13.1712 (±5.29)
I	Influx of population	LU=0.20%yr^{-1}(± 0.10); LU_{peak}=4.99% (± 1.96); LU_{start}=1980 ; LU_{end}=2000
II	Uptake of drugs before stricter drug testing	k_1=98.83% (± 0.94); k_2year=1989
III	Formation of WADA	k_2=99.12% (± 0.63); k_1year=2000
IV	Olympic Games	Amp, A=0.16% (± 0.22)
V	World Championships	Amp, C=0.15% (± 0.26)
	Goodness of fit	R^2=0.980; R^2_{adj}=0.977; MSE =0.004%; SSE=0.19%

Figure 6.32: Final improvement function model for the men's 800 m running event

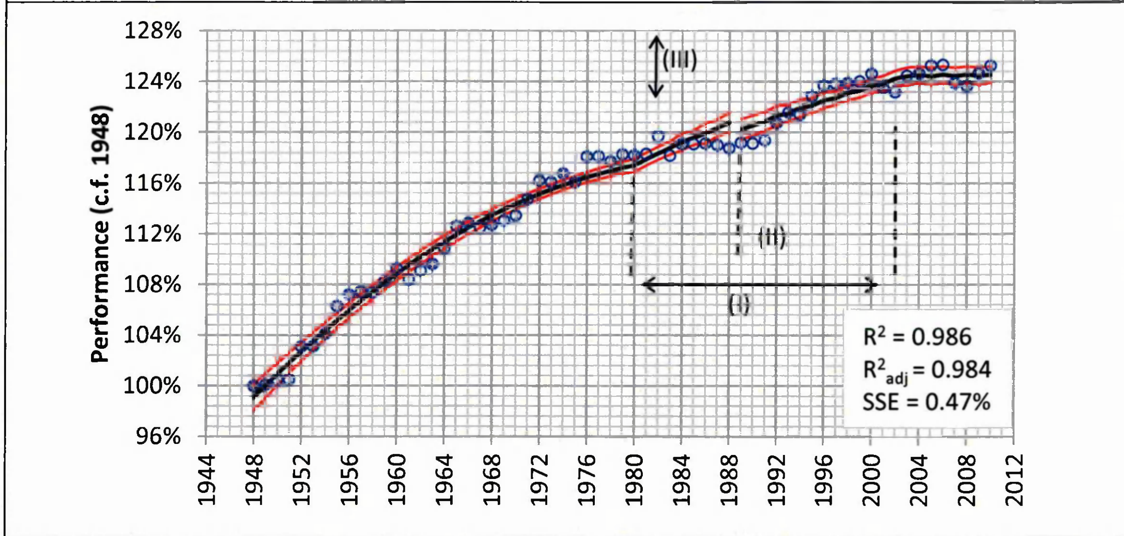
Men's 1500 m



	Intervention	Parameters
	Global improvement	L=115.67% (± 1.41); a=0.0491 (± 0.03); b=11.7386 (± 4.94)
I	Influx of population	LU=0.22%yr^{-1}(± 0.10); LU_{peak}=4.32% (± 2.03); LU_{start}=1980 ; LU_{end}=2000
II	Uptake of drugs before stricter drug testing	k_1=98.65% (± 1.02); k_2year=1989
	Goodness of fit	R^2=0.981; R^2_{adj}=0.979; MSE =0.006%; SSE=0.34%

Figure 6.33: Final improvement function model for the men's 1,500 m running event

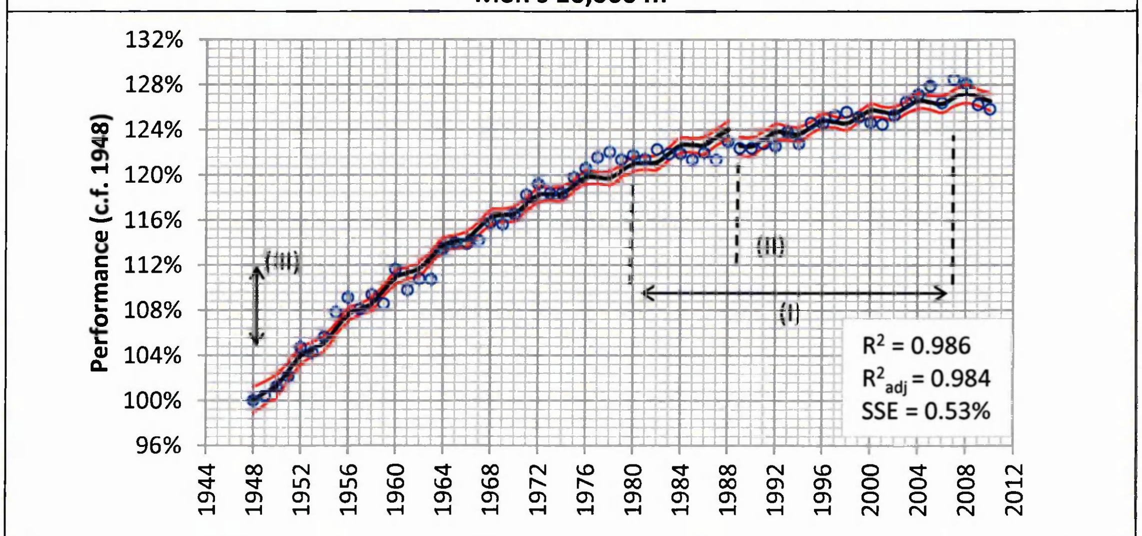
Men's 5000 m



Intervention		Parameters
	Global improvement	L=119.18% (± 1.37); a=0.0224 (± 0.01); b=17.9597 (± 6.96)
I	Stricter drug testing	k_1=99.32% (± 1.12); $k_1 year$=1989
II	Influx of a population	LU=0.27%yr^{-1}(± 0.09); LU_{peak}=6.19% (± 2.13); LU_{start}=1980 ; LU_{end}=2003
III	World Championships	Amp, C=0.052% (± 0.39)
		R^2=0.986; R^2_{adj}=0.984; MSE =0.008%; SSE=0.47%

Figure 6.34: Final improvement function model for the men's 5,000 m running event

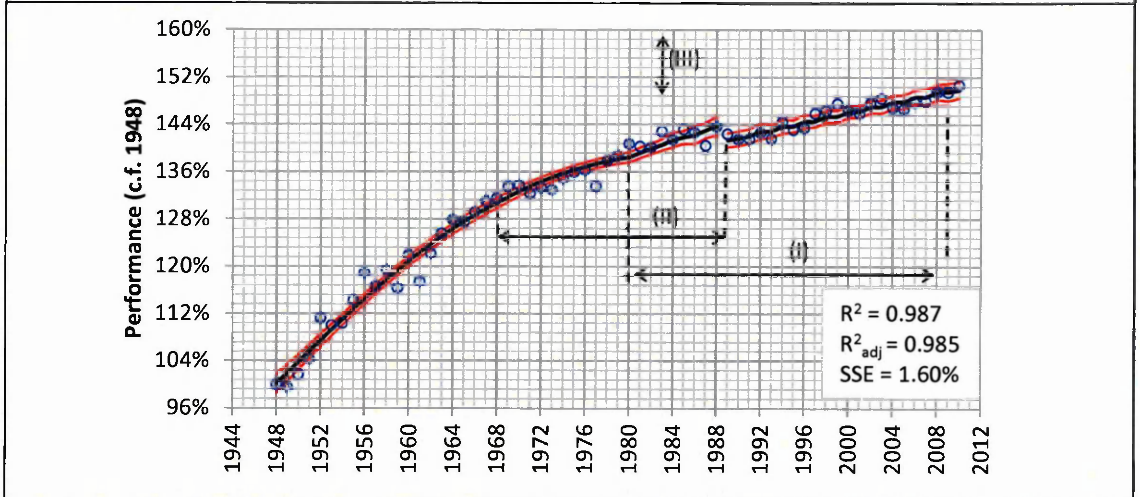
Men's 10,000 m



Intervention		Parameters
	Global improvement	L=122.83% (± 1.48); a=0.0173 (± 0.01); b=20.0284 (± 8.36)
I	Stricter drug testing	k_1=98.89% (± 1.07); $k_1 year$=1989
II	Influx of a population	LU=0.20%yr^{-1}(± 0.08); LU_{peak}=5.51% (± 2.18); LU_{start}=1980 ; LU_{end}=2007
III	Olympic Games	Amp, A=0.36% (± 0.35)
		R^2=0.986; R^2_{adj}=0.984; MSE =0.009%; SSE=0.53%

Figure 6.35: Final improvement function model for the men's 10,000 m running event

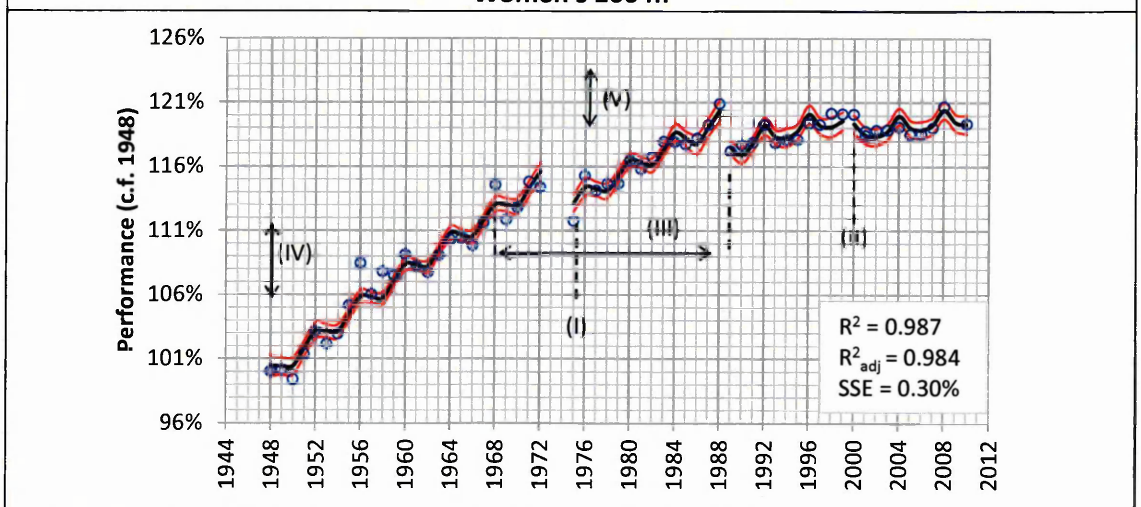
Men's marathon



Intervention		Parameters
	Global improvement	L=137.71% (± 2.06); a=0.000603 (± 0.0004); b=147.6914 (± 69.58)
I	Influx of a population	$LU=0.41\%yr^{-1}$(± 0.10); LU_{peak}=12.02% (± 2.92); LU_{start}=1980 ; LU_{end}=2009
II	Uptake of drugs before stricter drug testing	$D=0.13\%yr^{-1}$(± 0.12); D_{peak}=2.66% (± 2.32); D_{start}=1968 ; D_{end}=1988
III	World Championships	Amp, C=0.17% (± 0.70)
		R^2=0.987; R^2_{adj}=0.985; MSE =0.03%; SSE=1.60%

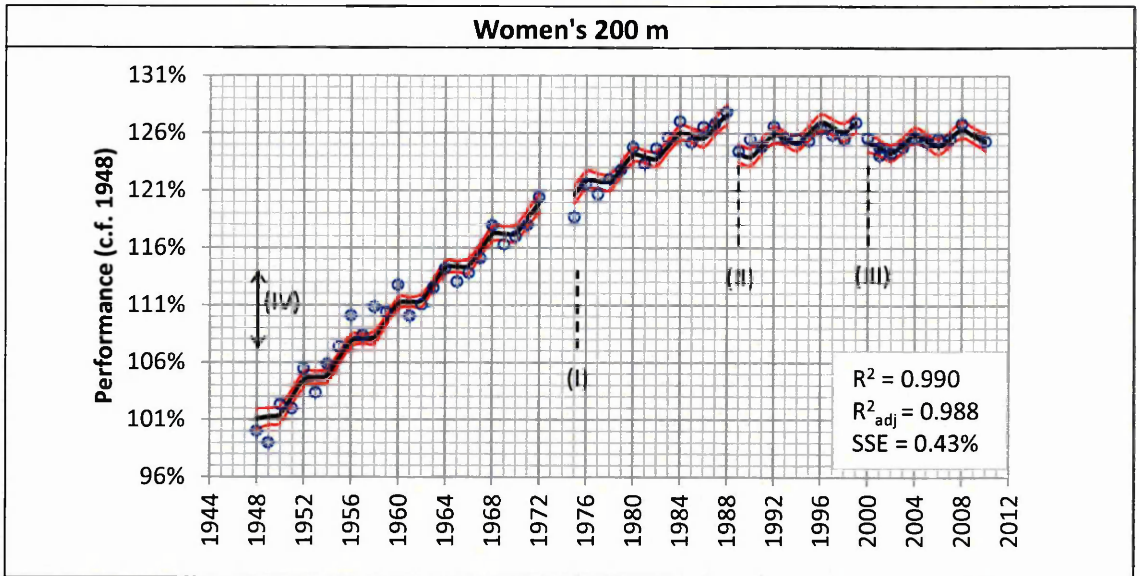
Figure 6.36: Final improvement function model for the men's marathon running event

Women's 100 m



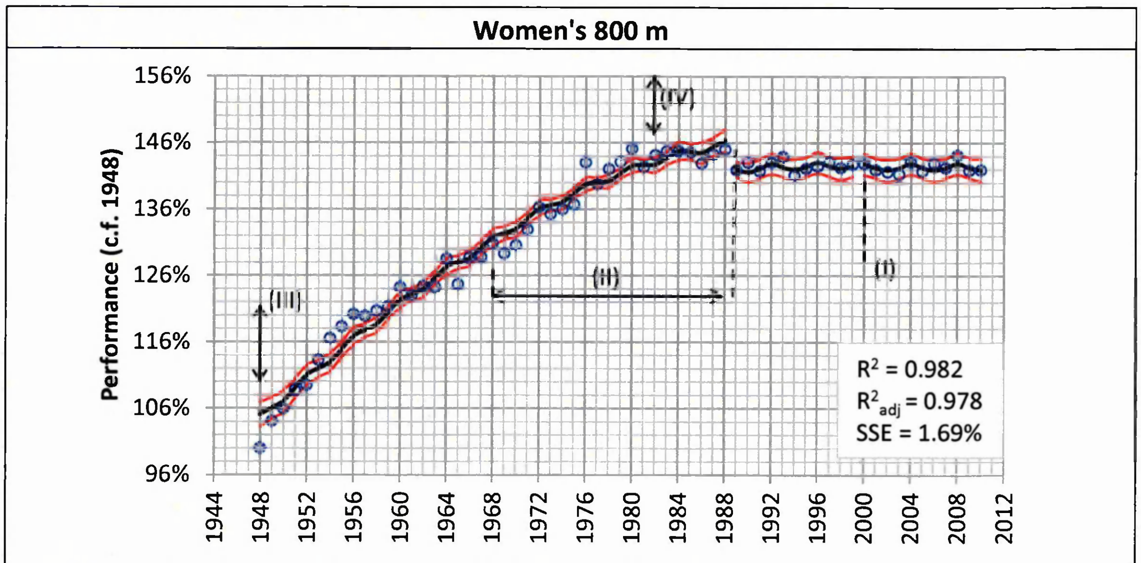
Intervention		Parameters
	Global improvement	L=126.02% (± 2.97); a=0.0700 (± 0.02); b=7.3340 (± 1.48)
I	Fully automatic timing	k_1=96.96% (± 1.11); k_1year=1975
II	Formation of WADA	k_2=95.79% (± 1.58) k_2year=2000
III	Uptake of drugs before stricter drug testing	$D=0.12\%yr^{-1}$(± 0.06); D_{peak}=2.38% (± 1.15); D_{start}=1968 ; D_{end}=1988
IV	Olympic Games	Amp, A=0.71% (± 0.31)
V	World Championships	Amp, C=0.21% (± 0.35)
	Goodness of fit	R^2=0.986; R^2_{adj}=0.983; MSE =0.006%; SSE=0.33%

Figure 6.37: Final improvement function model for the women's 100 m sprint event



	Intervention	Parameters
	Global improvement	L=133.07% (± 4.54); a=0.0331 (± 0.009); b=10.7846 (± 2.37)
I	Fully automatic timing	k_1=99.60% (± 1.14); k_1year=1975
II	Stricter drug testing	k_2=97.53% (± 1.12); k_2year=1989
III	Formation of WADA	$k3$=97.96% (± 1.01); k_2year=2000
IV	Olympic Games	Amp, A=0.66% (± 0.35)
	Goodness of fit	R^2=0.988; R^2_{adj}=0.986; MSE =0.009%; SSE=0.50%

Figure 6.38: Final improvement function model for the women's 200 m sprint event



	Intervention	Parameters
	Global improvement	L=142.65% (± 1.33); a=0.0024 (± 0.001); b=57.1990 (± 19.55)
I	Formation of WADA	k_1=99.80% (± 1.46); k_1year=2000
II	Uptake of drugs before stricter drug testing	D=0.19%yr^{-1}(± 0.10); D_{peak}=3.95% (± 1.95); D_{start}=1968 ; D_{end}=1988
III	Olympic Games	Amp, A=0.49% (± 0.65)
IV	World Championships	Amp, C=0.08% (± 0.76)
	Goodness of fit	R^2=0.982; R^2_{adj}=0.978; MSE =0.03%; SSE=1.69%

Figure 6.39: Final improvement function model for the women's 800 m running event

6.12 Results - Interventions modelled

The results gained from the fitting of the final improvement function model to each of the running events examined will be explored and discussed in this section. The first intervention to be examined is the influence of fully automatic timing introduction within the sprinting events.

6.12.(a) Fully automatic timing

6.12.a.(i) Results – Fully automatic timing

The influence of fully automatic timing or FAT was modelled with a step change in 1975, as this was the year at which all performances in the top twenty five were to two decimal places indicating the use of fully automatic timing. Shown in Table 6.8 is the magnitude of the influence of fully automatic timing in terms of percentage decrease in performance improvement index and raw performance time in seconds.

Table 6.8: The magnitude the effect of the introduction of fully automatic timing systems modelled with a step change in 1975, shown with 95 % confidence bounds

	Intervention size (PII %)	+/-	Intervention size (s)	+/-
100 m - men	-3.8%	0.7%	0.20	0.04
200 m - men	-2.7%	0.7%	0.29	0.08
400 m - men	-2.3%	1.0%	0.54	0.23
100 m - women	-3.0%	1.1%	0.18	0.07
200 m - women	-0.4%	1.1%	0.05	0.14

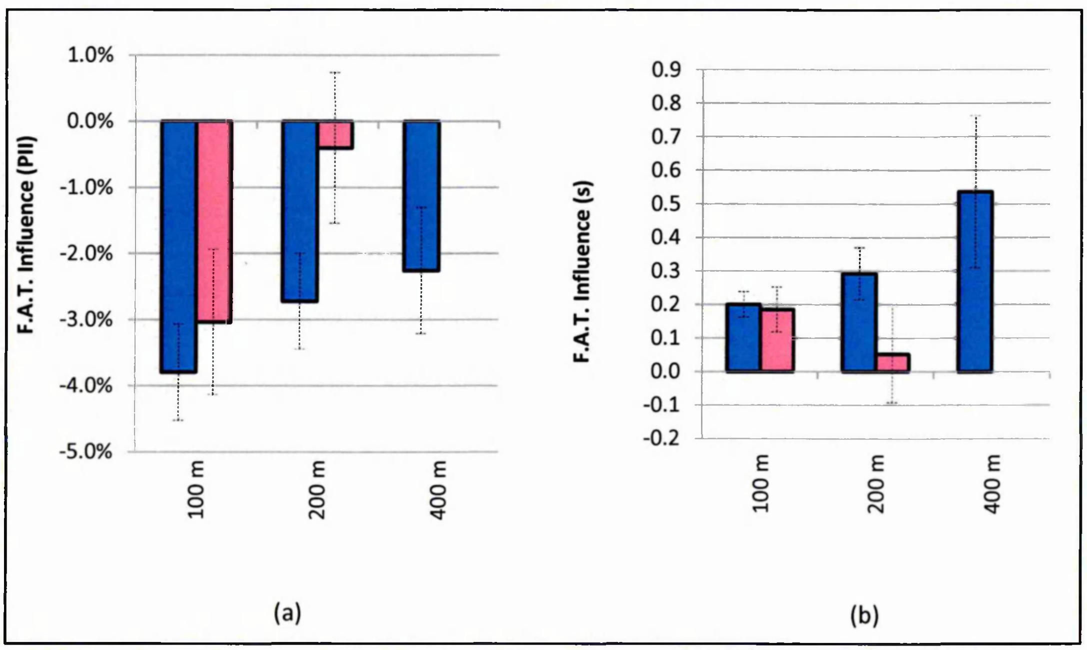


Figure 6.40: The magnitude of the effect of fully automatic timing introduction modelled with a step change in 1975 shown in units of (a) PII and (b) raw time in seconds

6.12.a.(ii) Discussion – Fully automatic timing

The step change used to model the influence of the introduction of fully automatic timing was found in all events examined for this influence. The greatest influence terms of percentage decrease in performance was in the 100 m men's event at -3.8 (+/-0.7) % meaning that this event saw the greatest influence from fully automatic timing. This step change is shown visually in Figure 6.29 depicting the final improvement function of the 100 m men's event. The lowest influence in terms of performance decrease was in the 200 m women's event, at -0.4 (+/-1.1) % meaning this event saw the least influence from fully automatic timing. The actual magnitude of the effect of fully automatic timing varied from -0.05 (+/- 0.14) seconds in the women's 200 m to -0.54 (+/-0.23) seconds in the men's 400 m. As the final step change parameters used to model the introduction of fully automatic timing were all negative, it appears that fully automatic timing has had a negative influence on athletic performance in these sprinting events. As fully automatic timing is a passive technology and cannot directly influence sporting performance, the performance drop is only an artefact the technology introduction, and does not mean actual performance has decreased. Nevertheless the influence of fully automatic timing technologies needs to be gauged and understood as performance times in 1948 collected without the use of fully automatic timing need to be compared to modern day times which were collected with the use of fully automatic timing.

The apparent drop in performance from the introduction of fully automatic timing was originally attributed to the reaction time of the starting judge in starting the stopwatch, and therefore in theory the magnitude in terms of seconds of this effect should be the same or similar across all events (assuming timing judges react to the visual smoke of the gun). In spite of this the effect of fully automatic timing has been previously stipulated to be -0.24 seconds in the 100 m and 200 m and -0.14 seconds in the 400 m (IAAF 2012, ATSF 2012), these figures have been used by statisticians and likely originate from an obscure study carried out at the 1972 Munich Olympic Games and reasons behind the variation in FAT adjustment figures are therefore not known. These original figures used to account for FAT are not too dissimilar to the figures found here, but it seems that the within this study the effect of fully automatic timing in terms of raw time is greatest in the 400 m rather than the 100 m and 200 m. It is possible that the original figures used to account for FAT are not accurate.

A diagram of the differences between manual timing and automatic timing is shown in Figure 6.41. The reaction time and error in prejudging the finish are small effects, and a higher proportion of the total running time the shorter this total race time. This is why there is a less effect in terms of performance improvement in percentage the longer the race as we see in this study, and theoretically in events lasting more than minute such as the 800 m and longer the effect of fully automatic timing is so small it is an insignificant factor in terms of performance improvement. This might be the reason why original factors used by track and field weekly were lower for the 400 m. This is backed by examining the number of fully automatic times in the top 25 lists over the transition period between hand held recorded times to that of automatic times. In the 400 m men's event some fully automatic timing results metres which are now believed to be negative influenced by FAT made it in to the top 25 three years earlier than the other sprinting events in 1971. This could mean that the effect of FAT in the 400 m men's event of 2.3 % could more easily overcome by other improvements such as better training, track conditions or wind conditions during the race.

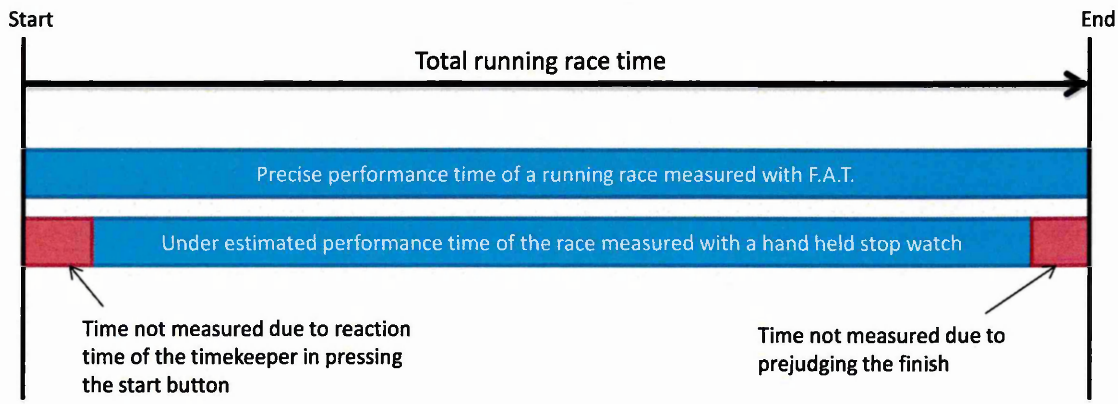


Figure 6.41: Total time and measured time of a fully automatic timing system as well as a manual system to measure the length of a race

The effect of fully automatic timing found in this study in terms of raw time is highest in the 400 m men's event and this could be because of another thus far over looked factor which comes with hand timing, the error in judging the finish. It seems that time keepers tend to prejudge the finish of a race, and stop their timekeeping devices slightly earlier (McCrory 2005). If we assume that the distance that time keepers prematurely judge the finish of a race is constant the differences found in magnitude of the effect of fully automatic timing can partly be explained by the different speeds of running races. If the prejudgement distance to the finish of a race was set, the average speed of a men's 400 m race in 2010 for the top 25 at 8.92 ms^{-1}, the time taken to cover this final 1 metre in 400 m would be 0.22 seconds (2dp). The same for the 100 metres at an average speed for the top 25 in 2010 of 10.01 ms^{-1}, the last 2 metres will be covered in 0.20 seconds (2dp). In reality this effect is likely to be larger as the 400 m sees a greater deceleration phase at the end of the race when compared to the 100 m.

However this difference in finishing speed and the prejudgement of a finish still does not fully account for the large step change parameter for fully automatic timing influence in the 400 m when compared to the other events. Examining the 95 % confidence intervals surrounding the step change parameters there is a large error value associated with FAT factors in the men's 400 m. The lower bound could be mean the effect of FAT fact could be as low as 0.25 seconds, brining it closer to the other FAT values found and in line with the and the original theory that the effect of FAT in terms of raw time is the same across all events.

The large error bounds seen in the 400 m arise from the other interventions that are modelled within the final improvement function, the linear uptake of drugs from 1968 to 1988 and then a step change in 2000 will have influenced the 1975 step change factor. This highlights that additional modelling functions to account for other interventions change existing and increase the uncertainty of modelling parameters. This may also explain why women's events see a reduced the magnitude of the FAT influence. The linear uptake of drugs from 1968 to 1988 used in the women's 100 and 200 m may have obscured the 1975 step change modelling function accounting for FAT. This is a small problem with looking at this kind of performance data where interference of other influencing factors on athletic performance making it hard to distinguish individual magnitudes of interventions.

6.12.a.(iii) Conclusion – Fully automatic timing

In conclusion, FAT effect does exist within all the sprinting events examined and visually can be seen (Figure 6.29). The effect of fully automatic timing is similar across all events where an effect was modelled. This is attributed to timing delays caused by inherent human reaction time. Slight variations in the size of the fully automatic timing influence could be due prejudging the finish of the race and the early stopping of hand held watches. The faster running races may see less of an effect than the slower races.

Modelling evidence found here goes some way to question the magnitudes already assigned to the influence of FAT, however to gain accurate magnitudes a more detailed experiment is required.

6.12.(b) Usain Bolt effect

6.12.b.(i) Results – Usain Bolt effect

The effect seen in 2008 and designated the Usain Bolt effect was modelled with a step change in 2008 in the 100 m men's event. The magnitude of this intervention is shown below Table 6.9 in and represented graphically in Figure 6.42. An effect was not modelled in the 200 m as the model did not provide and improve fit.

Table 6.9: The magnitude of the Usain Bolt effect modelled with a step change in 2008, shown with 95 % confidence bounds

	Intervention size (PII %)	+/-	Intervention size (s)	+/-
100 m - men	0.7%	0.8%	-0.03	-0.04

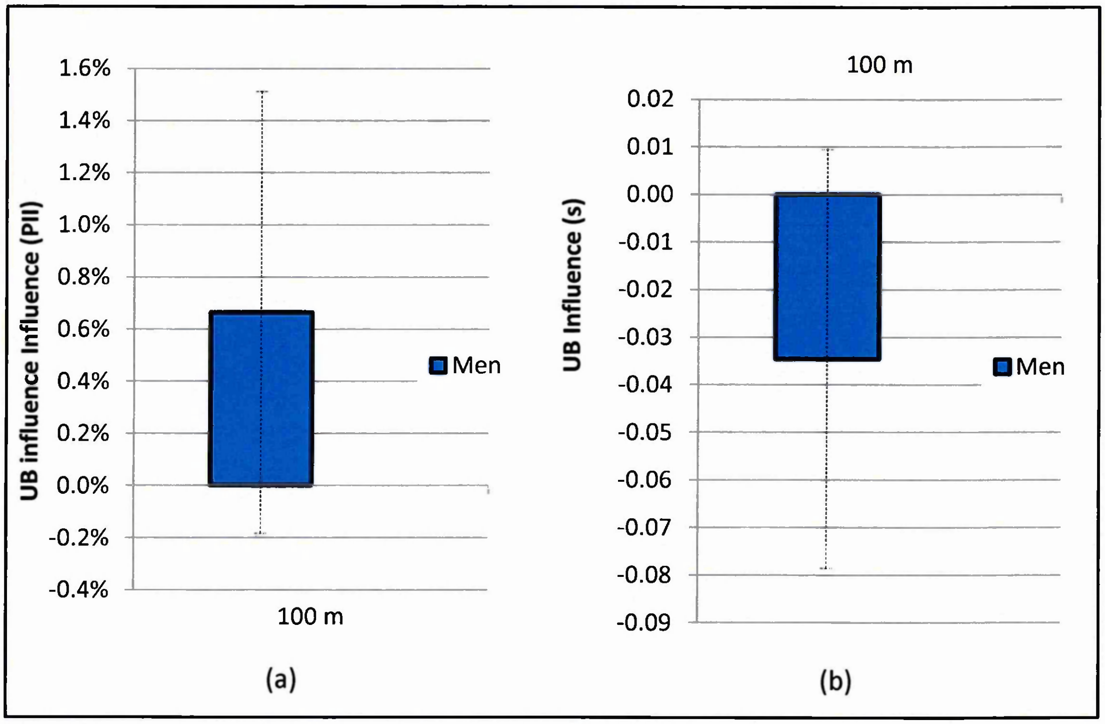


Figure 6.42: The magnitude of the Usain Bolt effect modelled with a step change in 2008 shown in units of (a) PII and (b) raw time in seconds

6.12.b.(ii) Discussion – Usain Bolt effect

The Usain Bolt effect modelled with a step change in 2008 for the 100 m men's event was shown to only improved the fit of the improvement function (increase in adjusted regression coefficient) in the 100 m and not the 200 m. This suggests that this effect is not just a Usain Bolt effect as he competed in both events. This means there must be another intervention which has only influenced the 100 m. The effect could be down to an increase in competitiveness throughout the 100 m elite field from the rise of Usain Bolt, but again this effect is not seen in the 200 m and the reasons why this is the case is not clear. On possibility is that Usain Bolt is a far superior athlete in the 200 m event. His improvements to the very top time did little to influence other athletes in the 200 m and therefore no effects could be seen in this event. However in the 100 m Usain Bolt was not initially the most dominant athlete, high levels of competitiveness in this event lead the entire top 25 times to display an increase in performance during the 2008 and subsequent seasons. This could have been as a result of Usain Bolt coming on to the scene.

The effect seen here is small, a 0.7 (+/- 0.8)% increase in terms of performance improvement and a possible drop of 0.04 (+/-0.04) seconds in performance time. In addition to this, large confidence bounds are seen within the step change parameter making it hard to definitely say that there is positive effect here. This step change could be modelling an additional Olympic effect in 2008, and brings up the problem again of modelling multiple interventions. The intervention is shown visually in Figure 6.29 and there does appear to be an effect occurring post 2008.

6.12.b.(iii) Conclusion - Usain Bolt effect

The reasons behind the step change that seems to occur in 2008 for the men's 100 m and the magnitudes of this effect are not clear. It is apparent that a step change occurs when visually examining at the data, but it has be found through a step change modelling function that the magnitude of this effect is small with large confidence bounds. The only way to see more clearly the magnitude of the step change in 2008 is to wait and gather future athletic data in the men's 100 m which will shrink error values making it easier to make firm conclusions.

6.12.(c) Linear population influx

6.12.c.(i) Results – linear population uptake

The influence of the influx of a new population, of runners representing African countries in the middle and long distance running events has been modelled with a linear uptake function. The start of the uptake function was applied in 1980 and ended at various years depending on whether the numbers of runners representing African countries reached saturation or completely filled the top twenty five lists. Shown in Table 6.10 is the start and end years used to apply the uptake function and the maximum effect seen from the function for each event. The results in this table have been shown graphically in Figure 6.43.

Table 6.10: The maximum magnitude of the influx of a new population effect, modelled with a linear uptake starting and ending with customised year, shown with 95 % confidence bounds

	Uptake start year	Uptake end year	Max intervention size (PII %)	+/-	Max Intervention size (s)	+/-
800 m - men	1980	2000	4.0%	2.0%	2.19	1.07
1,500 m - men	1980	2000	4.3%	2.0%	4.94	2.30
5,000 m - men	1980	2003	6.2%	2.1%	-26.54	9.01
10,000 m - men	1980	2007	5.6%	2.2%	-51.29	19.46
42,195 m - men	1980	2009	12.0%	2.9%	542.58	128.27

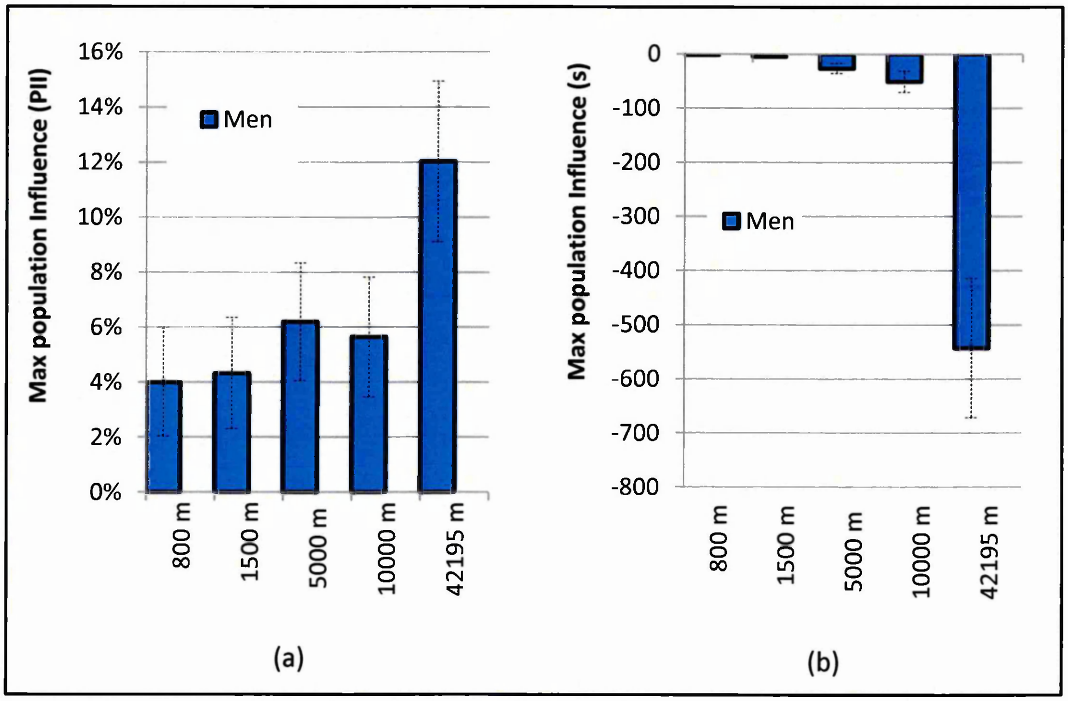


Figure 6.43: The maximum magnitude of the influx of a new population effect, modelled with a linear uptake starting and ending with customised year shown in units of (a) PII and (b) raw time in seconds

6.12.c.(ii) Discussion – linear population uptake

The greatest effect from the influx of the new population of runners representing African countries was in the men's marathon, with 12.0 (+/- 2.9) % performance increase. In the marathon the 12.0 % improvement relates to an actual performance gain of 542.58 (+/-128.27) seconds. The numbers of runners representing African countries in the top twenty five in the Marathon went from 0 in 1980 to all 25 in 2009. A medium effect was seen in the other two long distance events, the 5,000 m saw an increase in performance of 6.2 (+/- 2.1) % and the 10,000 m saw an increase of 5.6 (+/- 2.2) %. The top twenty five lists were saturated with all 25 runners representing African countries in 2003 and 2007 respectively.

The linear population uptake effect was not seen in the only women's middle distance running event examined, the 800 m. Women runners representing African countries have only started to start appearing in earnest in the top twenty five lists over the past few years and no significant effect as yet has been seen on performances. This just may mean that the women's 800 m may be lagging behind all men's events in terms of the numbers of African runners competing as there may be less emphasis and money spent on women athletics when compared to men in these African countries. There is no data collected as yet for the marathon or other long distance women's running events but it is expected that a similar improvement in performance will correspond with an increase in women African runners competing.

Only time will tell whether there is a population uptake effect in the 800 m and other women running events, with future performance statistics and uptake of African women runners into the competing population.

Shown now in Table 6.11 is the percentage increase in performance per African runner increase in the top twenty five lists. The percentage increase per African runner was simply calculated by the dividing the maximum estimated performance increase by the maximum number of African runners in the top 25. These figures are then represented graphically in Figure 6.44.

Table 6.11: The improvement in performance per African runner increase in the top 25 list for the different men's running events

Event (m):	800	1,500	5,000	10,000	42,195
Max effect :	4.0%	4.3%	6.2%	5.6%	12.0%
Saturation number:	15	15	25	25	25
PII per African runner:	0.27%	0.28%	0.25%	0.22%	0.46%

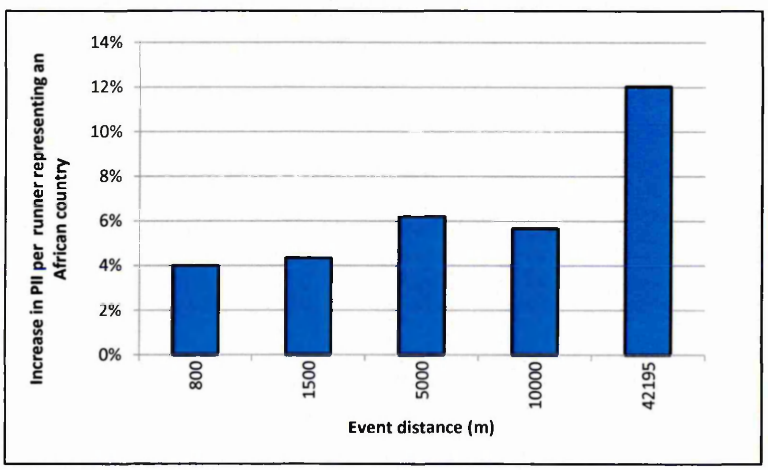


Figure 6.44: Performance improvement per African runner increase in the top 25 lists.

It seems that the 800 m o the 10,000 m saw a similar improvement per African runner increase at between 0.20 to 0.25 % per runner in the top twenty five. This is however not the same in the marathon where 0.46 % improvement is seen per increase in African runners in the top twenty five lists. This reiterates that the influx of African runners has had the greatest influence in the marathon event.

The final improvement function of the 5,000 m men's event is shown in Figure 6.34 and the linear uptake model can be clearly seen. It is apparent that the linear uptake over estimates performance levels at the start of the linear uptake as there is a delayed onset up linear increase. At the end of the linear uptake there is a slight underestimating of performance levels. The maximum magnitude of influence is unaffected by the simplicity of the linear uptake and was the original aim of the linear uptake model. The linear uptake model is good for the purposes of measuring absolute magnitudes from intervention uptakes, but may cause problems when assessing other interventions within the uptake period.

6.12.c.(iii) Conclusion

In conclusion it appears that a linear population uptake effect which models the increase of African runners and similar men's running performances in middle and long distance events can be seen. The men's marathon event seems to be influenced the most as this has been attributed to this event being the most prestigious, meaning there is a greater drive for African runners to compete in this event. There does not seem to be a measureable linear population uptake in the women's 800 m and this is attributed to the lower African female competing population which has only started to increase from the late 1980s at a slower rate than the men's events. This could mean that African female runners are lagging behind they male counterparts and in the future women's middle and long distance event will see a population influx effect.

6.12.(d) Drugs intervention: Linear uptake and step change 1989

6.12.d.(i) Results – Drugs linear uptake and step change 1989

The uptake of performance-enhancing drugs (and drug testing) has been modelled through the use of a linear uptake model from 1968 to 1988, followed by a step change in 1989 accounting for better drug testing technologies. The magnitude of the drugs peak in events where a linear uptake was found to model the uptake of drugs is shown in Table 6.12. Where a linear uptake model did not improve the fit of the improvement function, a single step change in 1989, accounting for better drug testing, was used. The magnitude of the individual step change in 1989 is shown Table 6.13. Both the step change and linear peak used to model of the effect of drug interventions are shown graphically in Figure 6.45, with cross hatched shading depicting the step change model effects. Four running events showed an enhanced fit using the linear uptake function combined with a step change. These were the men's 400 m and marathon, and the women's 100 m and 800 m. A step change without the linear uptake function was found to best model performance improvement in the men's 200, 800, 1500, 5,000 10,000 and 10,000 m and women's 200 m events.

Table 6.12: The magnitude of the introduction of new drug testing routines in 1989 modelled with a linear uptake of drugs from 1975-1988 and a step change in 1989, shown with 95 % confidence bounds

	Max Intervention size (PII)	+/-	Max Intervention size (s)	+/-
400 m - men	1.0%	0.9%	0.23	0.20
42195 m - men	2.7%	2.3%	122.63	106.67
100 m - women	2.4%	1.1%	0.14	0.07
800 m - women	3.9%	1.9%	2.76	1.35

Table 6.13: The magnitude of new drug testing routines effect, modelled with a step change in 1989, shown with 95 % confidence bounds

	Intervention size (PII)	+/-	Intervention size (s)	+/-
200 m - men	0.7%	0.8%	0.08	0.08
800 m - men	1.2%	0.9%	0.65	0.52
1,500 m - men	1.3%	1.0%	1.56	1.18
5,000 m - men	0.7%	1.1%	2.96	4.91
10,000 m - men	1.1%	1.1%	10.26	9.94
200 m - women	2.5%	1.1%	0.31	0.14

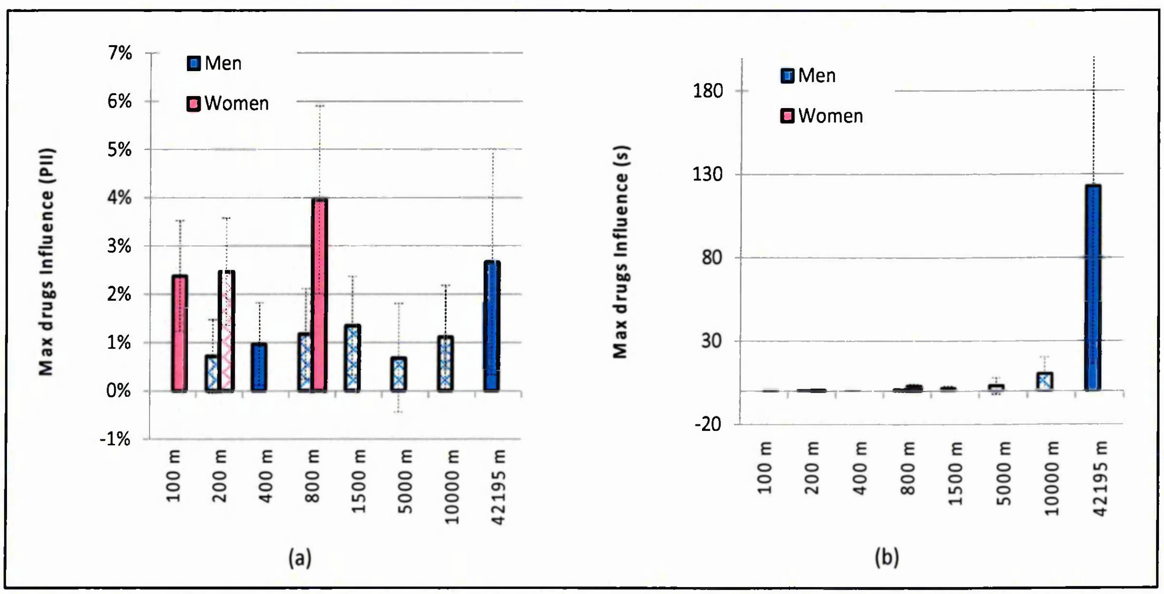


Figure 6.45: The magnitude of the linear peak (1968-1988) before a step change and an individual step change (1989) accounting for the uptake of drugs and better drug testing procedures in the running events where and effect could be measured, shown in units of (a) percentage improvement in the performance improvement index and (b) reduction of race time in seconds (NB step change magnitudes have been shown in the graph as crosshatched shading)

6.12.d.(ii) Discussion – Drugs step change 1989 alone

The men's 200 m saw a drop in performance of 0.7 (+/-0.8) % in 1989. There could be a drugs testing effect, but it is hard to say as the error bounds are so high (greater than the modelled effect). The women's 200 m event showed a drop in performance of 2.5 (+/-1.1) %, and was the only women's event which did not see an improvement in fit with a linear uptake of drugs function.

The men's 200 m is a similar event to the men's 100 m and many of the athletes compete in both events. The 100 m men's event did not see any effects as a result of drug testing procedural changes in 1989, from either a step change or a linear uptake and a step change. It is conceivable that there is not a noticeable influence from new drug testing procedures in 1989 on both these events

It is also believed that the men's 5,000 m and 10,000 m did not see an effect of drug testing procedural change in 1989 and the effect seen here is due to an incorrectly modelled linear uptake of the population model. Examining Figure 6.34, the final improvement function model for the men's 5,000 m, similar to the 10,000 m event the 1989 step change occurs in the middle of the linear population uptake. The linear uptake population model overestimated the performance improvement at the start of the linear uptake and an underestimation of performance improvements towards the end of the linear uptake. This error was due to the assumptions made when creating the linear uptake model and was expected. These assumptions are adequate for finding the peak influence from a linear uptake, however it seems that interventions such as a drugs step change that occur during the linear uptake cannot be accurately modelled and the effect in the 5000 m/10000 m is an artefact of the simplified linear uptake model used to model population uptake. It appears that it is difficult to quantify interventions across the linear uptake of population influx a more complex model such a sigmoidal curve will be required to model the population uptake more accurately.

6.12.d.(iii) Conclusion – Drugs step change 1989 alone

In conclusion although found to improve the fit of the improvement function in the events examined here It is not believed that in 1989 a step change accurately models the influence of drugs in the men's 200, 800, 1500, 5,000 and 10,000 m events and was mainly account for the inaccuracies of the linear population uptake model. The 200 m women's event appeared to show that the drug testing procedurals changes in 1989 did see a drop in performances and other women's events have been modelled with a more complex linear uptake and step change model to account for drugs.

6.12.d.(iv) Discussion – Drugs linear uptake with step change 1989

The greatest influence seen with this linear uptake and step change in 1989 model to account for drugs uptake and adoption of testing procedures was a seen in women's running events. It seems that all women's running events sprinting events saw a large detrimental effect with a peak value of drugs found in 1988 at 2.5 (+/-1.2) %, 3.2 (+/-1.3) and 4 (+/-2.5) % for the 100, 200 and 800 m respectively. The linear uptake model for drugs from 1968 to 1988 and a step change in 1989 is shown visually for the 100 m women's event in Figure 6.37.

The men's marathon also saw are large drop in performance with the advent of better drug testing procedures in 1989 and improvement function showing this drop is performance in 1989 in the men's marathon is clearly depicted in Figure 6.36. It could be possible that drugs such as EPO were used by middle and long distance runners (Trout & Kazlauskas 2004, WADA 2011).

6.12.d.(v) Conclusion – Drugs linear uptake with step change 1989

In conclusion the linear uptake of drugs followed by a step change in 1989 enhanced the fit of improvement function for quite a few events. Generally the women's events saw a greater improvement, which is in keeping with the other models to accounting for performance-enhancing drug use. The linear uptake part of this model allowed for a better fit as it modelled the deviation away from the global improvement exponential curve more accurately.

6.12.(e) Case study for Ben Johnson

It has become apparent that some doped performance times have been removed from the official record books. In 1988 Ben Johnson a Canadian sprinter set a time of 9.79 in the Olympic final. He later tested positive for Stanozolol a banned steroid and the Olympic gold medal he was stripped and given to Carl Lewis who finished second in the race (IAAF 2011). Another time set by Ben Johnson of 9.84 seconds in 1987 was taken off the records after he admitted taking performance-enhancing drugs.

These omitted times from the records books may indicate and vindicate the modelling steps used to model drug testing procedures and the influence of drugs in running events. Including just these two data points has shown to drop the raw performance times by -0.02 seconds in 1987 and -0.05 seconds in 1988 the Olympic year. The data for these calculations is shown in below Table 6.14.

Table 6.14: Modified mean of the top twenty five data points including Ben Johnson's banned times

Year	Ben Johnson doped top time (s)	Official mean of top 25 (s)	New mean of top 25 accounting for B.J. times (s)	Difference (s)
1987	9.84	10.08	10.06	-0.02
1988	9.79	10.11	10.06	-0.05

Unfortunately the step change in 1989 or linear uptake function accounting for the introduction of better drug testing procedures still do not show an improved fit with the two new data points calculated by the omitted doped times set by Ben Johnson. This could indicate that the athletes in the official top 25 lists in 1988 were all subject to the effect of performance-enhancing drugs, and Ben Johnson was the only athlete to get caught. Or the 1989 drugs testing effect is not apparent in 100 m men's sprinting events as the magnitude of the effect very small in comparison to other influencing factors.

6.12.(f) Drugs Linear uptake and decline (1968-1988-1999)

Applying the drugs linear uptake and decline model in step 7 for the sprinting running events and step 6 for the middle/long running distance events did not show an improvement in fit for the majority of running events. The men's 5000 and 10000 m did see and improvement in fit, but in these two events a negative linear uptake gradient was found to give the best fit. This was not the intended outcome of this model and indicates that this model for finding the influence of drugs uptake and then the uptake of better drug testing procedures did not follow a linear uptake and linear decline.

Drugs uptake and decline was not found in any of the running events examined, where drug influence is found it is modelled better with step changes or a single linear uptake and step change. This therefore indicates that the introduction of drug testing procedures had more of an instantaneous influence on running performances, but this may not be the case for other athletic events and is the reason why this modelling step was originally designed and implemented here.

6.12.(g) Drugs testing –Step 2000

6.12.g.(i) Results – Drugs step change 2000

Table 6.15 now shows the drop in performance in 2000 modelled with a step change that accounts for the formation of WADA the year before in 1999 and the centralisation of all drug testing programs. These results have then again been shown graphically in Figure 6.46.

Table 6.15: The magnitude of the effect of the formation of WADA, modelled with a step change in 2000, shown with 95 % confidence bounds

	Intervention size (PII)	+/-	Intervention size (s)	+/-
100 m - men	0.9%	0.8%	0.05	0.04
200 m - men	0.6%	0.7%	0.06	0.08
400 m - men	1.4%	0.7%	0.33	0.16
800 m - men	0.9%	0.6%	0.49	0.35
100 m - women	4.2%	1.6%	0.26	0.10
200 m - women	2.0%	1.0%	0.26	0.13
800 m - women	0.2%	1.5%	0.14	1.03

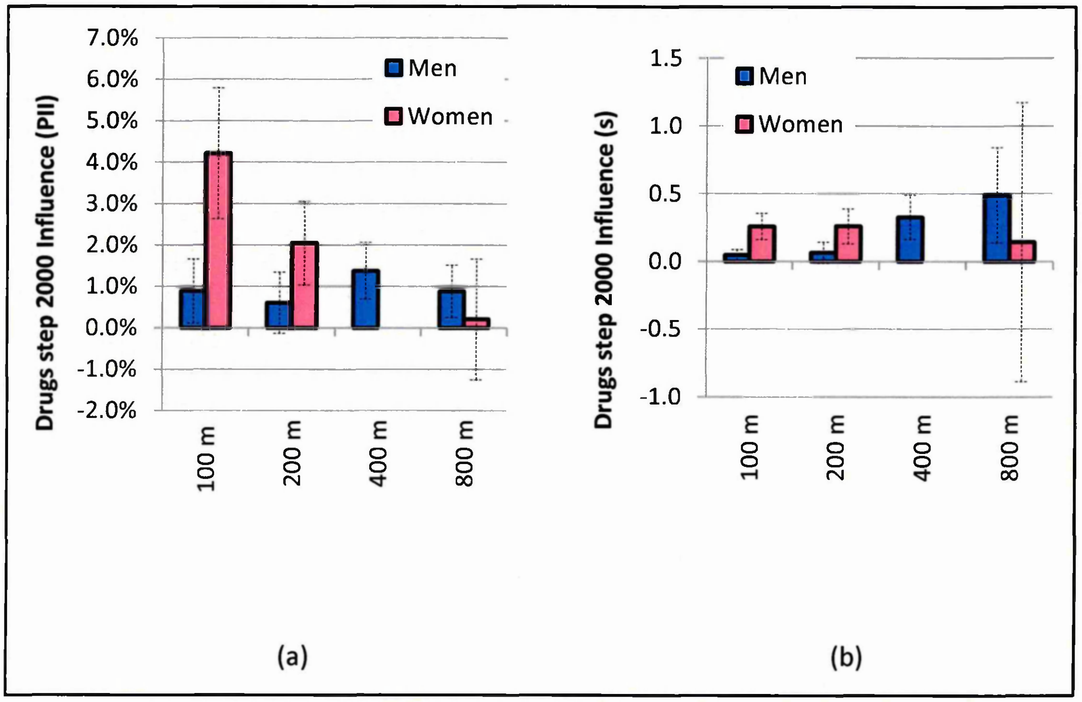


Figure 6.46: The magnitude of the effect of the formation of WADA, modelled with a step change in 2000 shown in units of (a) PII and (b) raw time in seconds

6.12.g.(ii) Discussion – Drugs step change 2000

The greatest influence from the step change used to model the formation of WADA was in the women's 100 and 200 m events at - 4.2 (+/-1.6) % and -2.0 (+/- 1.0) % respectively. It appears that all women events saw an a drop in performances with the formation of WADA in 1999, however in the women's 800 m the error bounds are larger than the intervention size and questions whether this intervention is present at all in these events.

All men's running event that were found to contain a 2000 step change show a lower influence than the women's events, with -0.9 (+/-0.8)% in the 100 m when compared to the women's 100 m which saw a drop of -4.2 % (+/-16). This indicates that drug testing procedures introduced in 2000 may have influenced women's performance to a greater extent than men's events. This ties in with the original theory that women are more affected by performance-enhancing drugs with effects such reduce fat mass, increase lean body muscle mass and increase hormone levels such as testosterone (Trout,& Kazlauskas 2004).

The effect of better drug testing procedures in 2000 was not found in any of the men's long distance events. It is possible that the influx of East African runners into these distance events masked the influence of new drug testing procedures, as it is apparent that the East African runners effect is so much greater than the influence of drug testing procedures found for other events.

The step change applied to the 100 m women's event is visually represented in the final improvement function for that event and is shown in Figure 6.37. It is believed that the 2000 step change used to account for the formation of WADA only influenced the high profile sprinting events for both men and women and not any of the middle and longer distance events.

6.12.g.(iii) Conclusion – Drugs step change 2000

In conclusion it is believed that a step change in 2000 due the centralisation and better drug testing protocols with the formation of WADA is seen in the sprinting events and possibly the 800 m. The 800 m events saw high error bounds for both men and women, meaning it is hard to say with any confidence that there is a 2000 drug step change in these events. Events from the 1500 m and upwards in distance saw no influence from better drug testing procedures in 2000 and could be masked by the influx of African runners.

6.12.(h) Olympic influence

6.12.h.(i) Results – Olympic Influence

Shown in Table 6.16 is the predicted magnitude of the Olympic effect, shown as an amplitude term from the sine wave model as well as a maximum effect which is double the amplitude term. This accounts for the sine wave moving from a trough to a peak. The max effect also incorporates the error value so that the Max effect = (amplitude + error) x 2.Figure 6.47 shows these values in a graphical form.

Table 6.16: The magnitude of the Olympic effect amplitude term, as well as the max Olympic effect from peak to trough as a % increase and raw time in seconds shown with 95 % confidence bounds

	Intervention size (PII)	+/-	Intervention size (s)	+/-	Max effect (PII)	Max effect (s)
100 m - men	0.33%	0.24%	0.02	0.01	1.1%	0.06
200 m - men	0.44%	0.22%	0.05	0.02	1.3%	0.14
400 m - men	0.43%	0.23%	0.10	0.05	1.3%	0.31
800 m - men	0.16%	0.22%	0.09	0.12	0.8%	0.42
10000 m - men	0.36%	0.35%	3.28	3.25	1.4%	13.06
100 m - women	0.71%	0.31%	0.04	0.02	2.0%	0.12
200 m - women	0.66%	0.35%	0.08	0.04	2.0%	0.26
800 m - women	0.49%	0.65%	0.35	0.46	2.3%	1.61

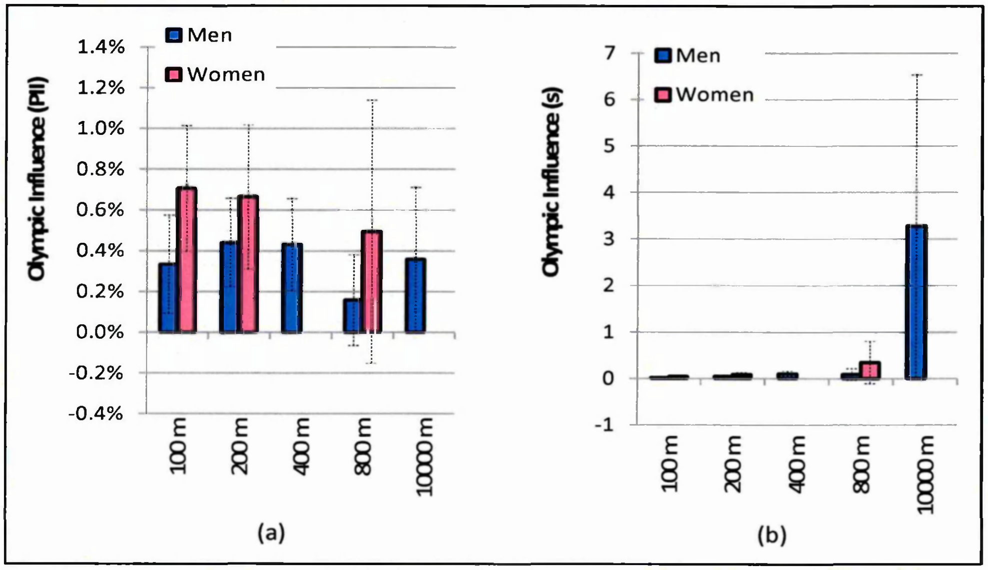


Figure 6.47: The magnitude of the Olympic effect shown in units of (a) PII and (b) raw time in seconds

6.12.h.(ii) Discussion

The majority of running events seem to experience an Olympic influence, with an increase in the goodness of fit value (adjusted coefficient of regression) for all running event apart from the men's 1,500 m, 5000 m and the marathon. However examining the confidence intervals we see that the men's 800 and 10,000 m as well as the women's 800 m show large confidence intervals for the predicted Olympic amplitude term, making it hard quantify the effect and questions whether there is an Olympic effect at all. This could indicate that an Olympic influence is not present in the middle and long distance running events, but present in the sprinting events.

There could be many underlying reasons for why the Olympic effect is seen in sprinting events but not the middle and long distance events. Firstly it is possible that the fame and prestige of an Olympic Gold medal in a sprint event is much higher than other events. These high prestige events may push sprinters to put all their efforts into

Olympic seasons as well as the Olympic final, pushing up performances. However for middle and long distance running events it could be difficult to tailor long term training programs and competition timetables so that peak performances are on the day of the Olympic final. Middle distance events are also very strategic and races are very tactical. Competitors in the Olympics may not want to produce their best time, but rather win the race by out sprinting another opponent to win a gold medal meaning they may not go all out to get the best time just do what needed to win the race.

In the marathon event other external factors such as the suitability of courses and external climatic conditions that occur at the Olympics could make it harder for athletes to produced peak performances. For example Marathon events are usually held in the middle of the day, specifically for television audiences. As the middle a summer's day in the majority of countries means that the climatic conditions will be too hot for marathon runners to perform at their optimum and hence marathon performance is reduced.

It also appears that the Olympic periodic effect is greater for the women's events examined. Women athletes may be more driven to compete at higher levels during Olympic Games seasons and during off seasons is competition not as important. One possible reason for this could be because women athletes may have breaks from competing in the time in the off seasons in-between Olympic Games and World Championships in order to raise families. This means peak performances during global championships years are emphasized and picked up with the model used in this study. The Olympic amplitude measured here with a sine wave function is very small in magnitude when compared to the size of other interventions.

6.12.h.(iii) Conclusion

It appears that there is an Olympic influence occurring in the majority of events. The only events where the Olympic effect was not found was in the men's 1500 m, 5000 m and marathon. In addition to this, it was hard to quantify the Olympic effect in the other middle distance events examined as there were high error bounds surrounding these parameters. The middle and long distance running events may not experience an Olympic effect due to the nature of these events. It may be hard to tailor long term training regimes to peak in Olympic Games seasons, conditions at Olympic Games could be detrimental and athletes may disregard Olympic Games and concentrate on producing their best performance at other events out of the Olympic season. Where the Olympic effect is found in running events, the magnitude of the effect it is small, ranging from 0.16 % to 0.71 %, or from peak to trough of the sine wave, 0.32-1.42 %.

6.12.(i) World Championship influence

6.12.i.(i) Results

Shown in Table 6.17 are the predicted magnitudes of the Athletics World Championships effect from 1983, shown as the amplitude term from the sine wave model as well as a maximum effect which is double the amplitude term accounting for the sine wave moving from a trough to a peak. Figure 6.48 shows these values in a graphical form.

Table 6.17: The magnitude of the World championship effect from 1983 in a 4 year period and 1991 with a 2 year period , shown with 95 % confidence bounds

	Intervention size (PII)	+/-	Intervention size (s)	+/-	Max effect (PII)	Max effect (s)
800 m - men	0.15%	0.26%	0.08	0.14	0.8%	0.45
5000 m - men	0.05%	0.39%	0.23	1.69	0.9%	3.82
42195 m - men	0.17%	0.70%	7.68	32.47	1.7%	80.30
100 m - women	0.21%	0.35%	0.01	0.02	1.1%	0.07
800 m - women	0.08%	0.76%	0.05	0.54	1.7%	1.18

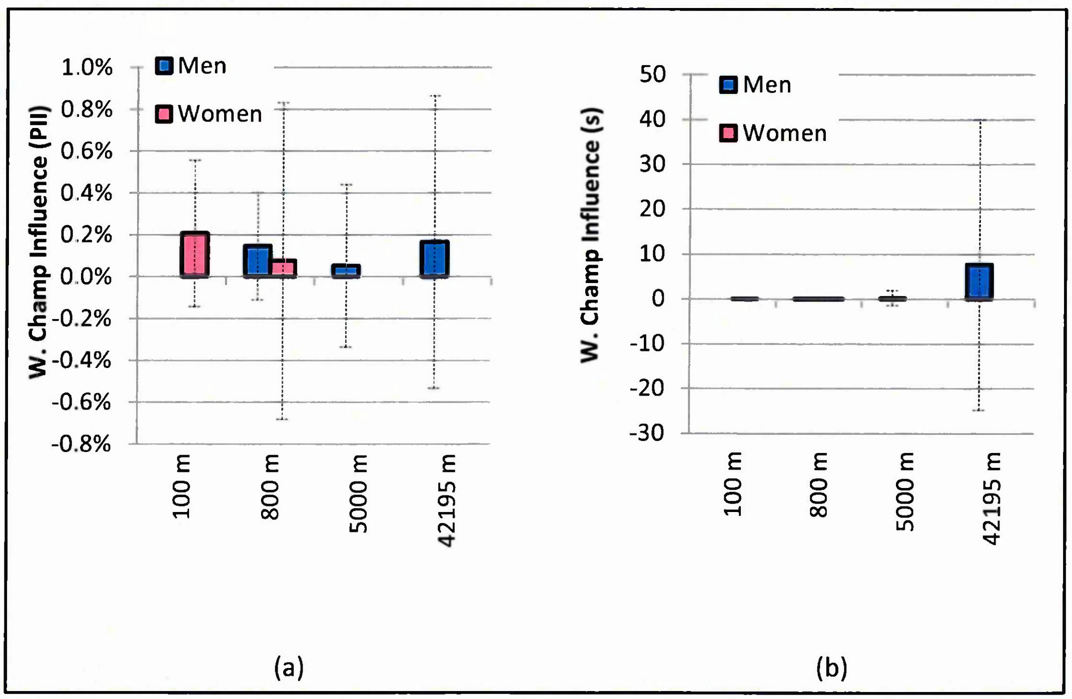


Figure 6.48: The magnitude of the World championship effect from 1983 in a 4 year period and 1991 with a 2 year period shown in units of (a) PII and (b) raw time in seconds

6.12.i.(ii) Discussion

A lot of the running events examined experienced an enhanced fit improvement function using a sine wave equation to account for the Athletic World Championships from 1983. All women's event saw an improvement in fit but only the men's 800 m, 5,000 m and the marathon saw a believed World Championship effect. It is interesting that the men's marathon event experienced a possible measured World Championship effect but did not experience an Olympic effect. This could indicate that the in the men's marathon there is more drive to produce peak performances during World Championship seasons, as there may be more incentives arising from greater prize and sponsorship money. A possible effect from World championships was also seen in the women's 100 and 800 m, but again confidence bounds are very high.

It appears that all events which saw and enhanced improvement function when considering the Athletic World Championship sine wave model from 1983 saw very large error values on the parameters calculated. These error values are all greater than the amplitude term and make it difficult to say whether there is an actual Athletic World Championship effect. At this detailed stage of the improvement function model small interventions model through a sine wave function could possibly be measuring noise and scatter of the data. As the Athletic World Championships effect found is very small and the uncertainty around the magnitude values are high it was decided not to continue modelling this effect in other events.

6.12.i.(iii) Conclusion

The men's marathon saw a World Championships effect and could be down to higher sums of prize and sponsorship money available out of Olympic Games years and in World Championships years. Women's events also see a World Championship effect and this effect is generally higher than the men's events and could be down to women athletes taking breaks in off seasons to raise families, emphasising peaks in competition years. However athletic World Championships are very hard to model and gauge, with the effect size being very small from 0.07% to 0.24 % and the error bounds being very large. It was decided not to model a World Championship effect in future improvement functions.

6.12.(j) Limits to athletic performance

6.12.j.(i) Results – Limits to athletic performance

The predicted improvement limit without the addition of external interventions has been defined by the magnitude of the final *L* parameter found in the global exponential improvement model. These *L* parameters for each running event are shown in Table 6.18 as a percentage increase from 1948, a raw time in seconds and a raw time in hours, minutes and seconds. The year at which the global improvement function is within 0.1 % of the predicted limit, is also shown in Table 6.18. It is assumed that inside 0.1 % of the predicted limit, the improvement function has practically reached the predicted limit.

Table 6.18: The predicted natural performance limits for all running events examined shown with year at which the improvement functions are within 0.1% of this limit and shown with 95 % confidence bounds

	L parameter (PII %)	+/-	(s)	+/-	Time (h:mm:ss.00)	Year when within 0.1% of limit
100 m - men	117.01%	3.52%	9.64	0.14		2061
200 m - men	117.25%	3.44%	19.62	0.51		2036
400 m - men	117.00%	2.73%	43.63	0.40		2040
800 m - men	115.57%	0.86%	104.94	0.40	0:01:44.94	1994
1500 m - men	115.67%	1.41%	214.62	1.31	0:03:34.62	2001
5000 m - men	119.18%	1.37%	797.10	4.57	0:13:17.10	1999
10000 m - men	122.83%	1.48%	1661.35	10.04	0:27:41.35	2000
42195 m - men	137.71%	1.67%	7918.72	59.21	2:11:58.72	1988
100 m - women	126.02%	2.97%	10.74	0.13		2031
200 m - women	133.07%	4.54%	21.84	0.37		2025
800 m - women	142.65%	1.33%	118.35	0.55	0:01:58.35	1997

Shown next in Table 6.19 are the predicted interventions that are believed to still be influencing running performances from 1948 and the adjusted predicted performance limit taking into account these interventions. It is assumed that any future running performance will not be influence by performance-enhancing drugs as they have conceivably been eliminated from performance lists with the advent of strict drug testing programs, new detection technologies and discouraging punishments. The only measureable interventions to currently influence running performance from 1948 other than the global improvement curve are: the so called Usain Bolt effect in the 100 m, fully automatic timing in sprinting events, population influx in the middle and long distance running events and finally the Olympic Games.

Table 6.19: New predicted running performance limits accounting for interventions since 1948

	L parameter		UB		FAT		LU Peak -		Olympics		New limit with interventions		
Event	PII	(s)	PII	(s)	PII	(s)	PII	(s)	PII	(s)	PII	(s)	h:mm:ss.00
100 m - men	117.01%	9.64	0.70%	0.03	-3.8%	0.20			0.3%	0.02	113.7%	9.79	
200 m - men	117.25%	19.62			-2.7%	0.29			0.4%	0.05	114.5%	19.86	
400 m - men	117.00%	43.63			-2.3%	0.54			0.4%	0.12	114.8%	44.05	
800 m - men	115.57%	104.94					4.0%	-2.19	0.2%	0.09	119.7%	102.66	0:01:42.66
1500 m - men	115.67%	214.62					4.3%	-4.94			120.0%	209.68	0:03:29.68
5000 m - men	119.18%	797.10					6.2%	-26.54			125.4%	770.57	0:12:50.57
10000 m - men	122.83%	1661.35					5.6%	-51.29	0.4%	3.45	128.8%	1606.61	0:26:46.61
42195 m - men	137.71%	7918.72					12.0%	-542.58			149.7%	7376.14	2:02:56.14
100 m - women	126.02%	10.74			-3.0%	0.18			0.3%	0.02	122.5%	10.91	
200 m - women	133.07%	21.84			-0.4%	0.05			0.7%	0.08	133.2%	21.81	
800 m - women	142.65%	118.35							0.5%	0.35	143.2%	118.00	0:01:58.00

6.12.j.(ii) Discussion – Limits to athletic performance

The year at which these global improvement values are reached vary from event to event. Some events seem to show that they will reach a theoretical performance improvement limit in the future such as the 100 m men's event which is predicted to plateau in 2058. Other events, the middle and long distance events seem to have already surpassed a predicted global limit, such as the men's 800 m in 1988, men's 1500 m in 1992, the men's marathon in 1988 and the women's 800 m in 1996. If these events had been left to evolve naturally from 1948 without any external interventions, these are possibly the years when performance in these events would have plateaued. However, with the addition of external interventions, such as the influx of a new competing population, the predicted global limits have increased. It is difficult to say whether these predicted limits are accurate and at what point they will be reached. For example there appears to be a current uptake of runners of East African descent in the women's 800 m. Therefore in this event performance is likely to increase in the future with a kind of delayed linear increase in performance due to this population influx. How this will alter the performance limit in the women's 800 m is hard to predict and means it is difficult to predict any future running limits without knowing what interventions may come in the future and how these will affect running performance.

The overall result of all the additional interventions upon running performance has increased the predicted performance limit, increased the percentage performance increase from 1948 and reduced performance times. In the sprinting events there have been some small influences from such step change interventions as fully automatic timing introduction and the Usain Bolt effect (only in the 100 m men's event). These step changes have not changed the predicted year at which the performance level is reached, only the magnitude of the performance limit.

The linear increase due to a population influx has increased the performance limit in the middle and long distance events. As the linear uptakes are assumed to have now stopped in the men's middle and long distance event's prior to 2010 these event may have now reached their predicted performance limit. However it is hard to say whether a linear uptake of African runners is still going on, with an increase in the numbers of African runners in extended top performances lists. An increase in African runners across the spectrum of top performance lists will likely increase performance at the top end of performance lists, by increasing competitiveness and thus increasing performance from all runners. In essence it is hard to say whether these events have actually reached a performance limit. This is the same for the 800 m women's event, where it appears that an influx of African runners has only just started influencing running performances and may still continue after 2010. It is hard to say when a population influx in the women's 800 m will stop influencing and increasing performance. Therefore the year at which a performance limit is reached and the magnitude of this performance limit in the women's 800 m is difficult to gauge.

After performance limits have been reached it is envisaged that competitions between athletes will become closer and closer, as the best athletes will have almost identical maximum performances. Performances will not now show an increasing trend only vary on a seasons by season basis, with an Olympic season likely to increase a performances limit further still. However these fluctuations due to Olympic competitions will be small and in the order of less than 1 %.

6.12.j.(iii) Conclusion – Limits to athletic performance

It seems that the global improvement function reaches a predicted limit value at various points for different events. All the sprinting events for both men and women appear to reach a limit at some point in the future, with the men's 100 m expected to reach a limit in 2058. The addition of linear uptake models to account for the influx of new population in middle and long distance events has suggested that the global predicted limit has already been reached in these events. Performance has only increase beyond these limits due to an external intervention which was not available in 1948, the addition of a new population of runners to the competing population.

Performance limits are influenced by interventions and interventions have generally increased the predicted limits. However it is hard to predict the absolute limit of human performances as the interventions that may occur in the future, and will influence running performance in an unknown way.

6.13 Chapter summary

Performance data for a range of men's and women's running events have been collected and results presented. It has been found that all running events follow a similar exponential trend which has been attributed to global improvement factors such as increases in the size of the competing population or improvements in training techniques. The Performance improvement index was applied to the running performance data in order to normalise the data and allow for inter event performance comparison. It has been found that increase in the performance improvement index varies from event to event. The variations in performance improvement indices have been attributed to the baseline performance figures used in the ratio calculations.

Some baseline figures from events such as the men's marathon seem not be at comparable performance levels.

It appears that the women's running events examined all peak in the 1980s prior to any widespread drug testing interventions. This may mean that women's running performance is more influenced by performance-enhancing drugs and can be attributed to increases in lean body mass associated with using these type of drugs.

Interventions within the athletic sport of running have been gauged through the methods described in chapters three, four and five, and it has been found that technology has most certainly influenced running performance. There is an apparent drop in measured performances from the introduction of fully automatic timing systems in sprinting and an underground effect from performance-enhancing drug uptake and then subsequent improvements in drug testing techniques which are believed to have removed performance-enhancing drug effects. In addition to this an Olympic Games and Athletics World Championship influence is believed to be found most events. However the Athletic World Championship effect is hard to gauge as parameter error values are greater than the modelled effect. A summary of the interventions found and their believed range of influence is shown in Table 6.20.

Table 6.20: Summary of interventions found within the athletic sport of running and their range of predicted influence in term of percentage change in the performance improvement index.

Event	Intervention gauged	Effect size (PII) %
100 m	Usain Bolt named effect	0.7%
100 m , 200 m & 400 m (men and women)	FAT	-0.4% – -3.8%
Men's 800 m, 1500 m, 5000 m, 10,000 m & Marathon	Linear population uptake	4.0% – 12.0%
	Drug testing (1989 and 2000)	0.2% – 4.2%
Men's 400 and Marathon, Women's 100 m and	Drugs peak after uptake	1.0% – 3.9%
Excluding men's 1500 m, 5,000 m and Marathon	Olympics	0.16% – 0.71%
All	Original performance limits	15.57% – 42.65%
All	New performance improvement limits	13.3% – 49.7%

The general interventions found to affect running performance will now be examined within a selection of athletic field events. Field events have been selected based upon the significance of technological interventions on performance levels within that specific field event.

Chapter 7: Field events - Throwing and Jumping

7.1 Introduction

Levels of technology influence are now going to be examined in athletic field events. Performance levels in some field events such as the long jump and shot put are believed to be influenced very little by technological interventions. However performance levels in other field events such as the javelin or the pole vault are envisaged to be greatly influenced by technological changes.

Field events can been broken down in to two different categories: firstly the jumping field events, such as the long jump, high jump and pole vault, and secondly throwing field events, such as the shot put, discus and javelin.

The levels of which technology influences each individual athletic field event is not known, so the overall aim of this chapter is therefore to gauge the level of influence any technological changes have on athletic field event performance. The aim of this chapter can be broken down in to the following specific objectives.

1. Explore the history, rules and intervention in the different athletic field events.
2. Describe the performance improvements seen in a selection of field events.
3. Apply the intervention modelling techniques to collected field events performance data.
4. Comment on the levels of performance improvement in the different field events that are attributed to the various interventions.

7.2 Field events

Field events are athletic events that do not take place on the track, but instead on a 'field' located within the confines or close proximity of the track. All field events are designed to enable athletes to compete against each other fulfilling the second and third part of the Olympic motto: "higher" and "stronger". Athletes in field events have to either gain the greatest distance in a throw or jump, or the jump the highest.

To enable athletes to produce their greatest performance all field events are broken down in to different rounds in competition. A round represents an attempt by an athlete to perform the field event. A number of rounds within a competition allow each athlete to gain the best possible performance with their throw/jump. Multiple attempts mean that athletes can put everything in to the each attempt. If an athlete makes a mistake or a foul, they can attempt another performance in a later round. In the first round of competition some athletes often perform a "banker" throw/jump where they gain a respectable performance but know they improve on this in later rounds. This is just in case the athlete does not manage to register a later attempted with a more risky maximal performance. There are numerous athletic field events each with a unique set of rules. Field events can be broken down in to two distinct categories, throwing events and jumping events. The first category that will be examined is the throwing events.

7.3 Field events: throwing

A selection of field throwing events was chosen to be examined based on the believed influence of technology within the sport. All field throwing events involve at least one item of technology, the throwing implement. The first event to be examined is the Shot Put.

7.3.(a) Shot Put

The shot put is a basic event with few rules, the objective being to launch or "put" a shot (a metal ball) as far as possible over a number of rounds within a competition.

7.3.a.(i) Origins of the Shot Put

Origins of the shot put event can be found in antiquity with Homer mentioning competitions of rock throwing by soldiers during the siege of Troy, however there was no mention of a shot put like event at the original Greek competitions. The first known events that resembled the modern day shot put event occurred in the middle ages where soldiers held competitions in which they hurled cannonballs. Modern day shot put competitions were first recorded in the early 19th century and formed part of the highland games in Scotland. Shot put competitions were also part of the British Amateur Championships beginning in 1866 (IAAF 2012). The shot put event was held at the inaugural modern summer Olympic Games back in 1896 for male athletes, but it was not introduced until 1948 for female athletes.

7.3.a.(ii) Current rules of the Shot Put

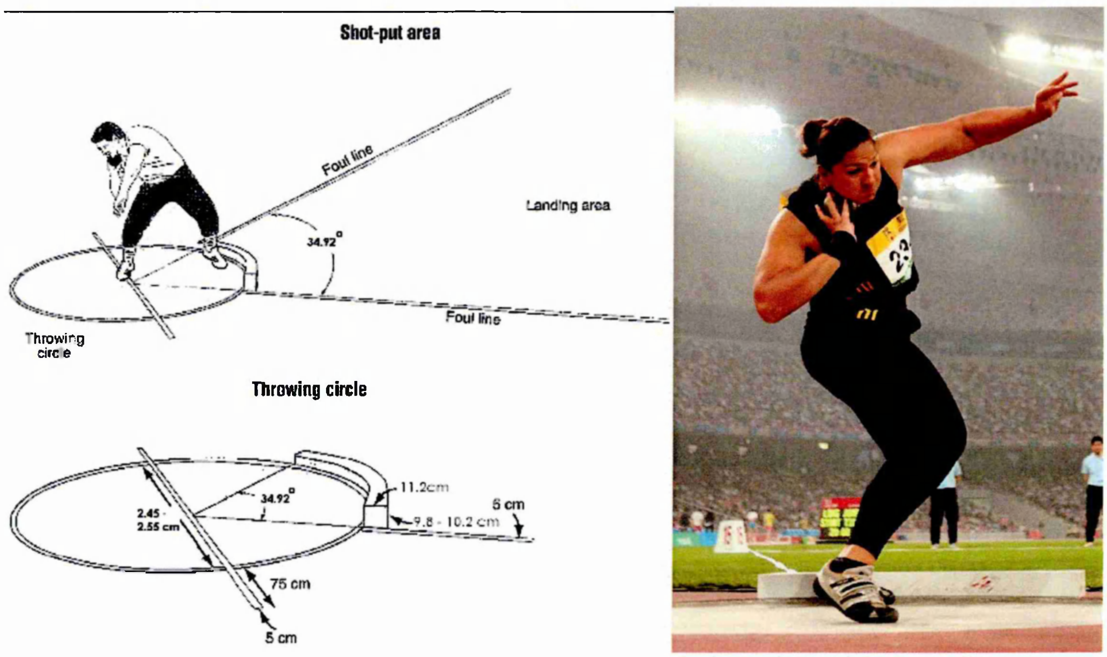
The shot put athlete has to perform the putting action within a circle measuring seven foot (2.13 m) in diameter. There is a stop board on the release side of the circle measuring approximately 10 centimetres high, this aids the thrower in the action of putting. A diagrammatical representation of the shot put throwing areas is shown in

Figure 7.1. (a). Additional rules of the shot put even include:

- Throwers should keep the close to the neck and keep it tight until the shot is released.

- The shot must be released above the height of the shoulder using only one hand.
- Throwers must not touch outside of the circle and stop board, but limbs may extend over the lines of the circle in the air.
- Men's shot weighs: 7.26 kg and Women's shot weighs: 4 kg

The distance of the shot put throw is measured from the edge of the circle directly to the back edge of where the shot put landed, or the nearest edge of the crater formed by the shot put as it landed. Distance measurements are made to the nearest centimetre.



(a) (b)

Figure 7.1 (a): Shot-put throwing circle and landing area (Athletics Australia 2011) , (b) Valerie Adams pictured performing the Shot Put event in the Birds Nest stadium at the 2008 Beijing Olympic Games. (IAAF 2010)

7.3.a.(iii) Putting techniques

There are two dominate techniques to putting, the Glide and the Spin techniques. The modern glide technique dates back to the 1950s when Pary O'Brien of the United states invented a technique in which a shot putter faced backwards at the rear of the circle bent down on the right leg (for a right handed thrower). Before releasing the shot put the shot putter will "glide and rotate 180 degrees towards the front of the circle before releasing the shot put.

The spin technique came about in the 1970s with both Aleksandr Baryshniko of the USSR and Brian Oldfield of the USA using such techniques. The spin differs from the glide technique as a shot putter rotates within the throwing circle to generate rotational momentum resulting in greater power when the shot is finally released. The technique is therefore more complex and also more inconsistent. For these reason the glide technique is popular with amateurs and many female throwers whereas the spin is popular with male professional throwers.

7.3.(b) Discus

The discus event is another throwing event where the objective is to propel a metal disc called the discus as far as possible over a number of rounds within a competition.

7.3.b.(i) Origins of the Discus

The discus event also traces its roots back to antiquity with a similar event held as part of the ancient pentathlon in Olympic Games competitions, dating back 708 BCE. Shown in Figure 7.2 is a depiction of a Greek discus thrower on the side of a vase.

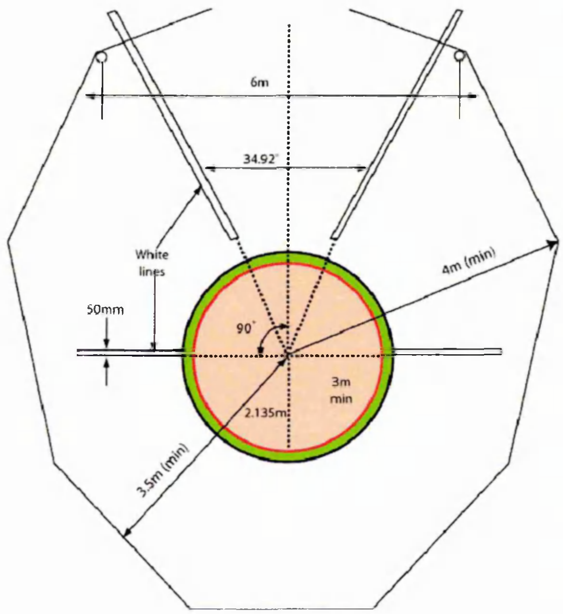
Figure 7.2: Ancient depiction on a Greek vase of a discus thrower, Tondo of Kylix (Louvre Museum)

The modern discus event was part of the first Olympic Games in 1896 for male competitors and was the first throwing event introduced for females in the 1932 Olympics.

7.3.b.(ii) Current Discus rules

The discus event is very similar to the shot put in that throwers perform the discus throw within a throwing circle using one hand. The throwing area of the discus however does not contain a raised stop board to aid athletes with a throw.

Figure 7.3 (a) shows the throwing area of the discus along with the dimension of the safety netting. Throws need to be completed within this area and stepping outside of this area during a throw makes that attempt a foul. The discus can land in any way and the distance from where the discus landed is measured to the edge of the circle to the nearest centimetre. The actual discus has now been standardised with the male discus weighing 2 kg and with a diameter of 219-221 mm. A lighter discus is used in the female event, weighing 1 kg and with a diameter of 180 – 182 mm.



(a) (b)

Figure 7.3: Throwing area of the Discus (Government of Western Australia, Department of sport and recreation 2011), (b) Jarred Rome of the USA competing in the Discus event at the 2007 World Athletics Championships at the Nagai Stadium in Osaka, Japan (Walton 2007)

7.3.b.(iii) Discus throwing technique

The technique in throwing the modern discus has evolved since the inauguration event at the 1896 Olympic Games. The basic motion of throwing the discus is a forearm throw, where the discus is released by the index finger of the throwing hand. For a right handed thrower the discus will rotate in a clockwise motion (or anticlockwise for left hand thrower) in flight. This spin is imparted by the index finger release.

The most up to date discus throwing technique involves various stages. The thrower starts at the back of the throwing circle facing away from the direction of the throw. In initiating the throwing technique the thrower then spins approximately 540 degrees (one and a half turns) before releasing the discus. The discus throw is a very difficult technique to master and as such the best throwers are usually over 30 years of age.

7.3.(c) Javelin

The javelin event is the last throwing event to be examined. The javelin is a long spear measuring approximately 2.5 metres in length, and this event has the same objectives as other throwing events, in that the objective is to throw the javelin the furthest distance over a number of competition rounds. Unlike the other throwing events javelin throwers utilise a run up to get the maximum distance in their throw.

7.3.c.(i) Origins of the javelin

The javelin event takes its origin from the one of the earliest technology devised by man, a spear, a simple hunting implement. There numerous ancient cave paintings which depict ancient humans using spear like implements to hunt. Today certain human populations still use spears to hunt and shown in Figure 7.4 is an Australian Aborigine using a spear to hunt.

Figure 7.4: Australian Aborigine Spear Hunting (Australian Adventures 2011)

The javelin is a slight evolution of the spear and is an offensive weapon used in earlier human warfare. It came to flourishing during the in Mycenaean Greece from about 1600 B.C.E. to 1100 BCE (Gardiner 1965). The javelin is lighter than the spear as this was found to be advantageous in gaining distance in the distance the javelin could be thrown. As such it was used a long distance attack weapon.

The earliest recorded javelin event was at the ancient Olympic Games competitions in Greece. Records show that the Javelin was part of the ancient pentathlon but it is unclear whether this javelin competition was judged by accuracy or distance (Gardiner 1965). The javelin was brought in to the modern Olympic Games athletic event program in 1908 in London for male athletes and in 1932 for females

7.3.c.(ii) Current Javelin rules

The javelin is the only throwing event where technique is dictated by the rules. This was due to possible safety issues arising with rotational throwing techniques such as the “Spanish javelin throw” that came about in the late 1950s. The IAAF moved to ban these techniques as they the direction of these throws were inconsistent and dangerous as stray javelins could travel into the crowd. The current rules stipulate that a thrower cannot turn their back so that it faces the direction of the throw. The only other rule regarding the actual throwing part of the throw is that the javelin must be held by the grip and thrown overhand over the throwers shoulder. Once a throw has been completed the javelin must land tip first to regard it as a legal throw. The length of the throw is measured directly from the arc to where the tip landed, so if the javelin was not thrown in a straight line there is no reduction in the measured distance.

The length of the javelin run way is 4 metres wide and no less than 30 metres long. The throwing area of the Javelin is a 29 degree segment in an arc from the end of the run way. A diagram depicting the Javelin throwing area and run way is shown in Figure 7.5 (a). The actual javelin for the men event is between 2.6 and 2.7 metres in length with a mass of at least 800 grams. A women’s javelin is between 2.2 and 2.3 metres in length and has a mass of at least 600 grams. Both javelins are equipped with a grip made of string and is located at the javelin’s centre of gravity. 0.9 – 1.06 m from the tip for men’s javelins and 0.8-0.92 metres for the women’s javelin.

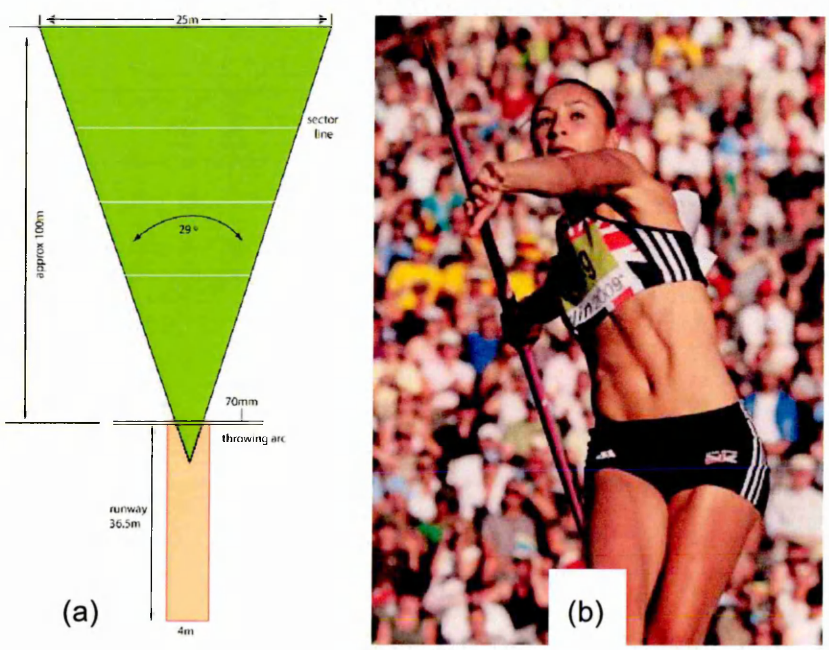


Figure 7.5: Run up and throwing area of the Javelin)Government of Western Australia, Department of sport and recreation 2011), (b) Jessica Ennis of Great Britain competes in the Javelin Throw of the women's Heptathlon at the World Athletics Championships 2009 in Berlin, Germany (The Independent 2009)

7.3.c.(iii) Throwing technique of the Javelin

As mentioned earlier, during the javelin event throwers utilise a runway to perform a run up before throwing the javelin. This run up enables the throwers to transfer more momentum in to the javelin enabling it to be thrown further. At the end of the run up throwers carry out a step routine in which their body rotates to one side. In doing this the javelin is taken back with a straight arm. Just before the throwing line, the thrower releases the javelin in an overhear arm throw. Shown in Figure 7.5 (b) is Jessica Ennis performing the last stages of a javelin throw at the 2009 World Athletic Championships.

7.4 Field events: Jumping

The second category of field events is the jumping events. These events require an athlete to jump as high or as far as possible depending on the specific event.

7.4.(a) Long jump

The long jump is similar to all throwing field events, in that the objective of this event is to jump as far as you can over a set number of rounds. Long jumpers run down a runway then launch themselves from a board in to a sand pit.

7.4.a.(i) Origins of the Long jump

Again the long jump finds its roots in the original Greek Olympic Games, being a part of the ancient pentathlon. The ancient long jump is thought to have also arisen from warfare and that the long jump event mimics the need to jump over obstacles on a battle field. Evidence shows that the original long jump event had a short run up and included the use of two hand held Halteres masses, a piece of technology which increased the length of the jump and shown in Figure 7.6. The long jump was part of the modern Olympic Games in 1896 for male athletes and for females the event was brought in, in 1928.

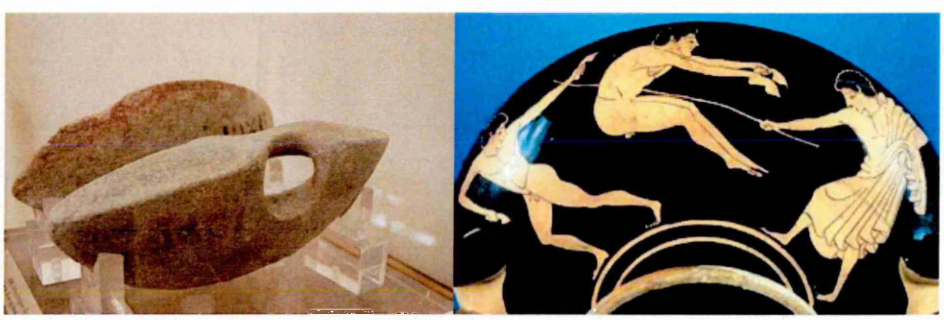


Figure 7.6: (a) Halteres masses used in the ancient Greek long jump event (National Archaeological Museum Athens) (b) Depiction of the of the ancient Greek long jump event on the side of a vase (Gardiner 1965)

7.4.a.(ii) Current rules of the Long jump

The long jump event takes place to the side of one of the main straights on a standard track layout. Long jump events take place on a runway in which jumpers run down to gain speed before they jump from a wooden board in to a sand pit. Jumpers can use two markers on the runway to assist with their jump and are allowed as much distance for their run up, within the runway boundaries.

The distance of the long jump is measured from the foul line to the nearest mark left by the jumper in the sand pit and is the nearest centimetre. If the jumper starts their jump at any point past the foul line, the jump is deemed to be foul. Officials judge the take-off by watching the jump and can clarify the exact point of take-off with the aid of a soft material directly after the foul line. Indentations are left in this material if a jumper strays over the foul line. As with the 100 and 200 metres sprinting events if a long jump is performed in a tail wind of greater than 2 ms^{-1} the jump is not valid.

7.4.a.(iii) Long Jump technique

The long jump, jumping technique is very simple, and can be broken down in to five different segments. Firstly the approach, this is where the jumper uses the runway to gain speed or translational energy before performing the jump. The second part is the transition between the running and jumping. The last two strides before the jump is where this happens. A jumper extends their last two strides and lowers their centre of gravity ready to spring up when they come in contact with the board. The take-off occurs following this stage and the jumper plants one foot as close to the board as possible and launches themselves upwards. This part gives the jumper the vertical component of the jump. The next section is flight section and the jumper uses various techniques to keep themselves from rotating forwards after the launch. There are various launch and flight techniques which a jumper uses. The final section is the landing and there are various techniques used by jumpers to avoid falling backwards to gain the greatest distance. Shown in Figure 7.7 is Jesse Owens in the flight section of his long jump technique, competing in the 1936 Berlin Olympic Games.

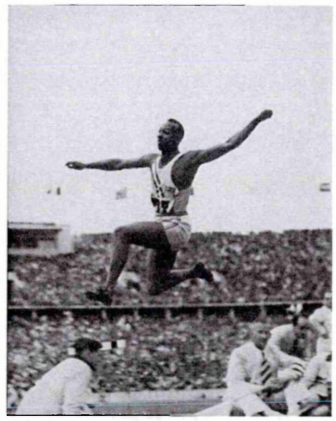


Figure 7.7: Jesse Owen competing in the Long jump event at the 1936 Olympic Games (Europeana blog 2011),

7.4.(b) High jump

The high jump is a jumping field event in which jumpers have to jump over a horizontal bar. The height of the bar is increased after each the round of competition and the athlete that attains the greatest height in the competition, with the least number of fails is declared the winner.

7.4.b.(i) Origins of the High jump

There is no clear evidence that an event resembling the modern high jump was part of the ancient Olympic Games (Gardiner 1965). There is evidence of a possible standing jumping technique without the use of Halteres, but it is not clear whether this was part of the training for the long jump or another standing long jump. Throughout the world, similar events to the modern high jump have existed for centuries. The Watusi tribe of central Africa practice a high jump event to train their warriors for war. A picture of a champion Watusi jumper is shown in Figure 7.8.

Figure 7.8: A Watusi champion high jumper, clearing a height of 2.57 m from a 0.12 m high take off stone (Willoughby 1970)

The first records of the modern high jump come from the 19th century at the Scottish highland games. The High jump was also at the inaugural modern Olympic Games in 1896 for male athletes. The High Jump was brought in later for female athletes in 1928. A standing high jump event was introduced at the second modern Olympic Games in 1900, but was later cut from the program after the First World War.

7.4.b.(ii) Current rules of the High jump

Essentially the high jump is a competition to see which athlete can jump the highest. It is difficult to measure the height of a jump directly as there is no way to physically mark a vertical jump. This is unlike the Long jump where sand in the long jump pit leaves a tangible marker for a distance to be measured. Instead the high jump competition is based around clearing a horizontal bar at a set height, and therefore slightly different to other field events.

Jumpers have three attempts to clear a height, before the height of the bar is increased in subsequent rounds. If the jumper fails all three attempts by knocking off the bar they are eliminated from the competition. The height of the bar keeps increases in later rounds and the athlete that clears the greatest height is declared the winner. If more than one jumper has achieved the same greatest height the winner is the jumper with the least amount of fails at that height. If there is still a tie, previous jump fails are counted. If the athletes still cannot be separated there is a sudden death jump off, where the height of the bar is alternatively increased and decreased until one jumper prevails (IAAF). Additional rules of the High jump include:

- The runway must be at least 15 metres long
- Jumpers are allowed to place two markers in the run up section to assist with their jump
- The cross bar is 4 metres long
- Shoe thickness cannot be more than 13 mm at the sole and 19 mm at the heel
- Jumper need to take off on one foot
- Heights are set to the nearest centimetre.

7.4.b.(iii) High Jump techniques

There have been various high jump techniques that have been employed by jumpers since the start of the modern Olympic Games. The more popular techniques evolved from the "Straight at bar" to the "Scissor" and then on to the "Straddle" of which the "Western" roll is a variant. Finally in 1968 Dick Fosbury won a gold medal at the 1968 Olympics using his newly developed high jump technique which was later renamed the

"Fosbury flop". High jumpers were amazed by this technique and soon all jumpers adopted this new technique. To this day the Fosbury Flop is still dominant technique used in the High Jump.

The Fosbury flop came about from the move to use safety mats to break a high jumper's falls after clearing the cross-bar in competitions. This meant jumping styles became more extravagant as jumpers were not worried about injuries that could have occurred in the old sand pits. The Fosbury flop involves the jumper running towards the cross bar in an arced trajectory. Upon reaching the cross-bar the jumper launches themselves off one foot and turns their back to face the bar. To get maximum height the jumper arches their back and bends their knees in passing the bar, thus reducing the height of the centre gravity which enables the jumper to attain a higher height. Using the Fosbury flop technique the jumper lands on their back on a safety mat. Shown in Figure 7.9 is Dick Fosbury performing the new high jump technique in 1968, which is now called the Fosbury Flop.

Figure 7.9: Dick Fosbury performing the Fosbury Flop in the High jump event (Britannica 2011)

7.4.(c) Pole vault

The pole vault event is similar to the high jump in that athletes attempt to clear a horizontal bar set at an increasing height over a number of rounds in a competition. Competitors competing within the pole vault event however make use of a piece of technology the pole and a straight up run up to assist with clearing the crossbar.

7.4.c.(i) Origins of the Pole vault

The pole vault event originates from the need to cross over or vault natural objects such as marsh land or small streams. There is no evidence that a pole vault event was part of the Ancient Olympic Games, but it was more than likely that a pole vaulting technique was used in in ancient warfare to clear moats or high walls. Due to the origins of the pole vault, early pole vaulting event must have been similar to the long jump, in that a pole was used to gain the greatest distance rather than height. At the Tailteann Games of Ireland of around 1829 B.C.E. there are records of a "pole-jump" but there is no reference to whether this event was a height or distance event.

Evidence suggests that the modern pole vault takes its origin from an event held at the Scottish highland games, and was part of the inaugural modern Olympic Games in 1896 for male athletes. For female athletes the Pole vault was only introduced at the Sydney 2000 Olympic Games.

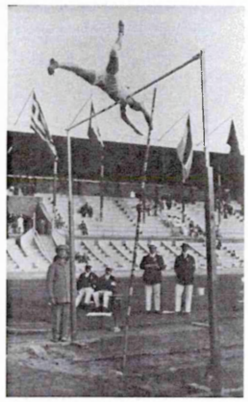


Figure 7.10 :Harry Babcock performing the Pole vault at the 1912 Olympics (Krupa 2009)

7.4.c.(ii) Current rules of the Pole vault

The pole vault is a very similar event to the high jump in that the vaulters compete in different rounds of a competition, and in each subsequent round the height of the cross bar is increased until a winner is declared.

Just like the high jump, vaulters in the pole vault are eliminated from the competition if they achieve three consecutive fails. However the Pole vault differs from the high jump as jumpers can pass at any point during the round, or pass the round entirely. Once a jumper opts in to a round they still only have up to three consecutive fails. If a jumper has made failed attempts in a previous round and as yet not achieved a height, these fails count towards the consecutive failed attempts.

If two or more vaulters have finished with the same height, the same rules occur as with the high jump event. The winner is the vaulter with the least amount of misses at the final height. If there is a tie, then fails from earlier rounds in competition count. If there is still a tie then like the high jump a jump off takes place. The runway of the pole vault event is at least 40 meters long and vaulters can place as up to two markers on the runway to assist with their vault. Competitors plant their poles in a one-meter long box that's 60 centimetres wide at the front and 15 centimetres wide at the back. The crossbar is 4.5 meters wide. A Pole vault, vault or jump is successful when the vaulter clears the cross-bar and it remains in place after the vaulter has left the landing area. There are some more specific rules of the Pole vault competition and these include:

- A fail is given to the vaulter if the vault has not been completed or passed within two minutes after being called.
- Additional weights cannot be used or other aids.
- Gloves or taping of the hands is not permitted.
- The vaulter's mass must be verified and correct pole rating used (IAAF 2011)

7.4.c.(iii) Pole vault technique

The modern pole vault technique consists of up to seven stages, these are: the approach, the plant and take off, hang, swing up, the extension, the turn, and finally the fly away. The approach shown in Figure 7.11 takes place from a standing start on the runway. The pole is initially held vertically, but lowered gradually throughout the approach section. Upon reaching within two strides of the planting box, the pole end is planted in to this box and the pole is pushed in front of the vaulter. At the take-off point the pole vault is now above the head of the vaulter and starts to bend as the vaulter lifts off the ground. When the vaulter is slightly off the ground the pole starts to bend and coverts the kinetic energy from the run up to stored strain energy within the pole. At this point the vaulter's centre of gravity is still kept as low as possible. The next section is the swing up, this is where the horizontal velocity has been almost reduced to zero and there is maximum bend in the pole, the vaulter then starts to swing upwards. Next the vaulter starts to extend their body, so that the legs reach as high as possible. This means the vaulter obtains an upside down position in the air. The turn happens during the extension phase and is where the vaulter spins their body around. The final part of the vault is when the vaulter has reached the top up the jump, and if successful has cleared the bar. The vaulter has now has fully turned in the air is facing back down the run way. The pole is then released and the vaulter falls on to their back on the crash mat. These phases of the pole vault technique are universal, but are often designated different names by coaches and athletes.

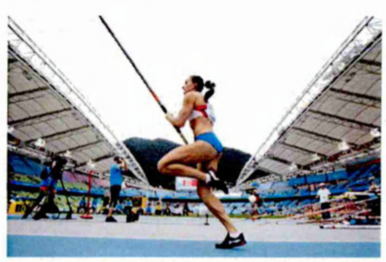


Figure 7.11: Yelena Isinbayeva of Russia in the approach section of her Pole Vault attempt during the women's pole vault qualifying event at the IAAF World Championships in Daegu, August 28, 2011 (Eurosport 2011)

7.5 Interventions in athletic field events

From 1948 there have been various historic intervening factors that have influenced athletic field event performance. These interventions have been summarised in the time line show in Figure 7.12 below.

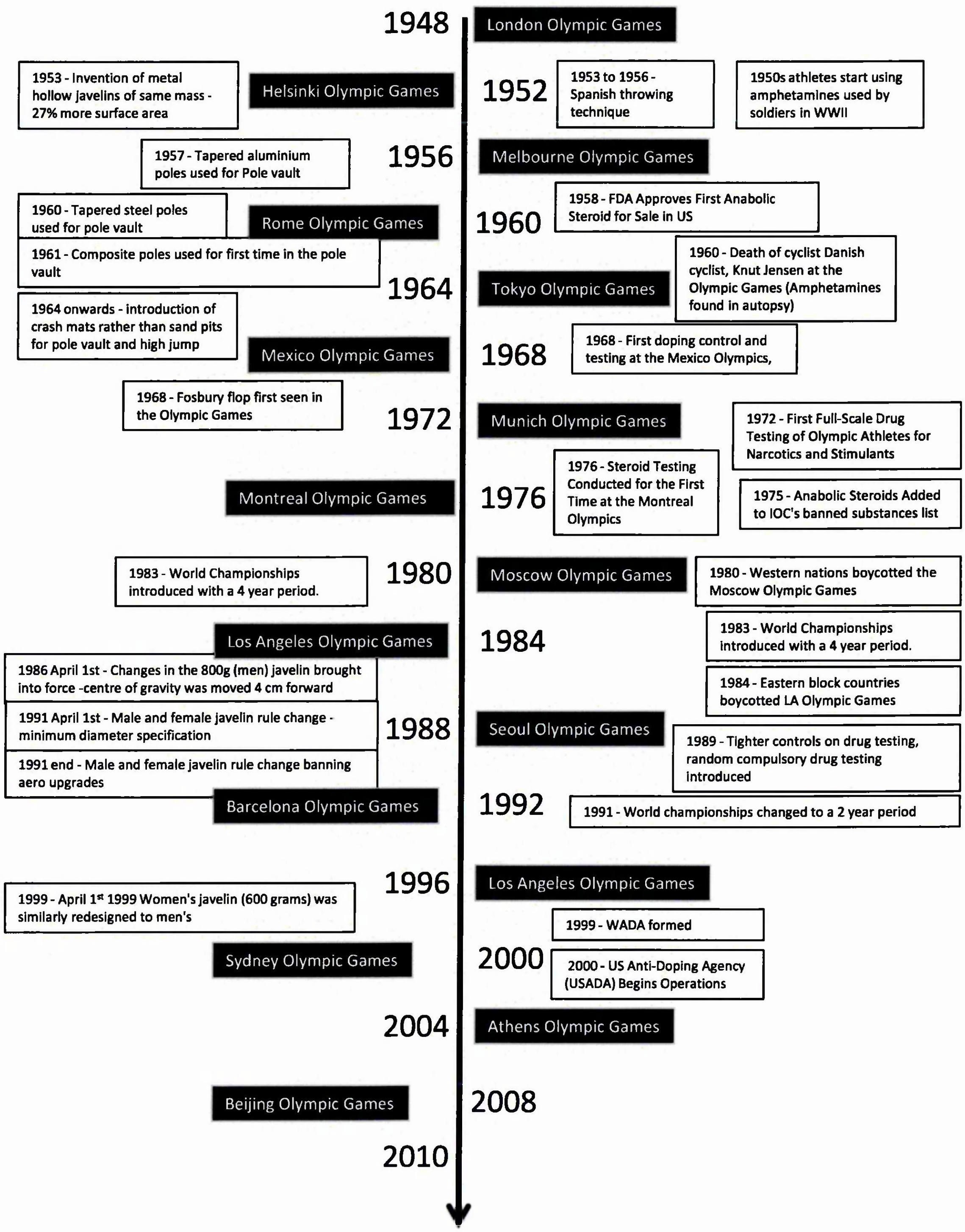


Figure 7.12: Time line of interventions from 1948 for athletic field events

7.5.(a) High jump technique

As with running events, different field events have specific technological interventions which have influenced performance since 1948. It is anticipated that high jump performance was influenced by a technique change called the "Fosbury flop" which was first seen in the 1968. When the Fosbury flop was first introduced there were other techniques employed by high jumpers and these other jumping techniques were also very efficient. The "Fosbury flop" slowly became the dominant technique used by high jumpers after it gained notoriety when Dick Fosbury won the 1968 Mexico Olympics high jump gold medal. However did the "Fosbury flop" actually have a measureable influence on the development of high jump performance, or could high jump performance continued to develop at a similar rate with the other available techniques?

7.5.(b) Pole technology

It is also believed that a technology introduction has also influenced the pole vault jumping event. The change in pole construction in the late 1950s and early 1960s is believed to have increased performances in the pole vault. Firstly in 1957 tapered aluminium poles were used and then later in 1960 tapered steel poles were used. The change from the original bamboo poles to metal poles is believed not to have influenced performance to a great extent and the pole vaulting technique stayed pretty much the same. The stiffness between bamboo and metal poles is believed to be similar and the reasons for the introduction of metal poles were due to the ease and consistency of manufacture as well as the added strength of the poles. In 1961 another change in the pole vault construction and materials came about. This was the introduction of composite poles, made with glass fibre and carbon fibre composite construction. These new poles are believed to have drastically changed the pole vaulting technique and improved performance. The new poles could flex to a much greater degree than existing poles and not break, meaning the new pole were now used as an energy storing device. The large flex in the pole now allowed the vaulter to convert more translational kinetic energy to vertical kinetic energy and then potential energy at the top of the vaulting technique, thus gaining a greater height. A diagram showing the different layers and construction of a modern pole vault is shown in Figure 7.13.

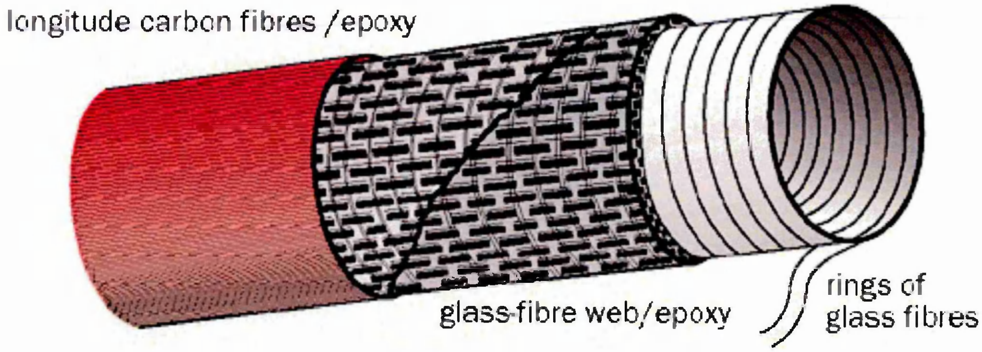


Figure 7.13: Modern composite pole construction (Material Solutions 2003)

7.5.(c) Safety mats

Safety mats have developed alongside the evolution of techniques and technology in the pole vault and high jump. Initially a landing pit filled with sand was used by vaulters and jumpers but as techniques developed and heights of these jumping events increases, the likely hood of gaining an injury from landing increased greatly. Safety mats were introduced around the mid-1960s to reduce the risk of injury and may have indirectly led to enhanced levels of performance.

7.5.(d) Hollow Javelins

In the early 1950s the javelin throwing event also saw a technological change concerning the construction of the javelin. To increase the distance of a javelin throw the surface area of the javelin was increased, allowing more for lift during the flight phase and thus increasing distance. To keep the new javelin mass constant and in line with the rules, the construction of the javelin changed and designers made the javelin hollow (IAAF). The increase in surface area of the javelin may have increased the measured performance in both the men's and women's javelin event.

7.5.(e) Spanish throwing technique

A new technique was used in the javelin event around the same time as the introduction of hollow javelin, however this technique was short lived and banned in 1956. The Spanish Javelin technique employed a full rotation before releasing the javelin, similar to the discus technique. This meant it was dangerous as the javelin could be released in any direction in to the crowd and for this reason was banned by the IAAF. Any influence on javelin performance was brief and it is believed that any visual effect on performance cannot be seen. A depiction of the Spanish javelin throwing technique is shown in Figure 7.14.

Figure 7.14: Depiction of the Spanish Javelin throwing technique (Track and field news 2011)

7.5.(f) Javelin specification changes

As javelin performances evolved, the greatest measured distance in the javelin event reached 104.80 metres in 1984 with a performance from Uwe Hohn. This throw distance was potentially dangerous for spectators and athletes within the athletic stadium and required change to improve safety. As athletic stadiums could not be increased in size, the obvious answer was to change the specification of the Javelin. The IAAF acted in changing the rules concerning the specification of the men's 800 gram javelin with the new rules coming in to force on the 1st of April 1986. The centre of gravity of the javelin was shifted 40 mm forwards, moving it away from the centre of pressure and leading to an increased downwards pitching moment during the flight phase. The rules were initially brought about due to disputes arising from the difficulties in judging the fairness of flat javelin landings, but had the added benefit of increasing safety by reducing javelin performance (IAAF). A similar rule change was implemented in the women's event in 1999, with the centre of gravity being move 30 mm forwards. A step drop in performance is therefore likely to be seen in the men's javelin event in 1986 and similarly in the women's javelin event in 1999 (IAAF).

To counteract the drop in performances due to the centre of gravity rule change in the men's javelin event the aerodynamics of the javelin was altered by designers to increase the throw distance once again. The tails of javelins in both the men's and women's events were made rougher to decrease the pressure drag in the hope to increase flight distances of the javelin. These changes were short lived and banned by the IAAF at the end of 1991 (IAAF). If tail roughness changes in the javelin influenced performances a step change in 1992 is likely to be seen.

7.5.(g) Performance-enhancing drugs

As with running events performance-enhancing drugs are likely to have influence all field event performances. For running events 1975 was used as the baseline start year for all drug uptake improvement functions. It was initially believed that drug influence could only be seen in women's running events from this date onwards, however it could be possible that performance-enhancing drugs have influence performance in field events earlier and a different start date for the drug uptake function could be used. For running events a decline function was not seen, however it could be possible that field events do have a decline in performance stage. With all running events believed to be influence heavily by drugs, a peak year of 1988 was seen. This may not be the case in field events and a peak year for the uptake of drugs function may need to be tailored for each different field event. This could be done by finding a peak year prior to 2000 for each field event. Global step changes in 1989 and 2000 due to the implementation out of competition random drug testing and the formation of WADA are also believed to influence field events and will also be examined.

7.6 Results: Field events raw performance

Raw field event performance improvement (mean of the top 25) over time has been displayed graphically for jumping events in Figure 7.15, and for throwing events in Figure 7.16.

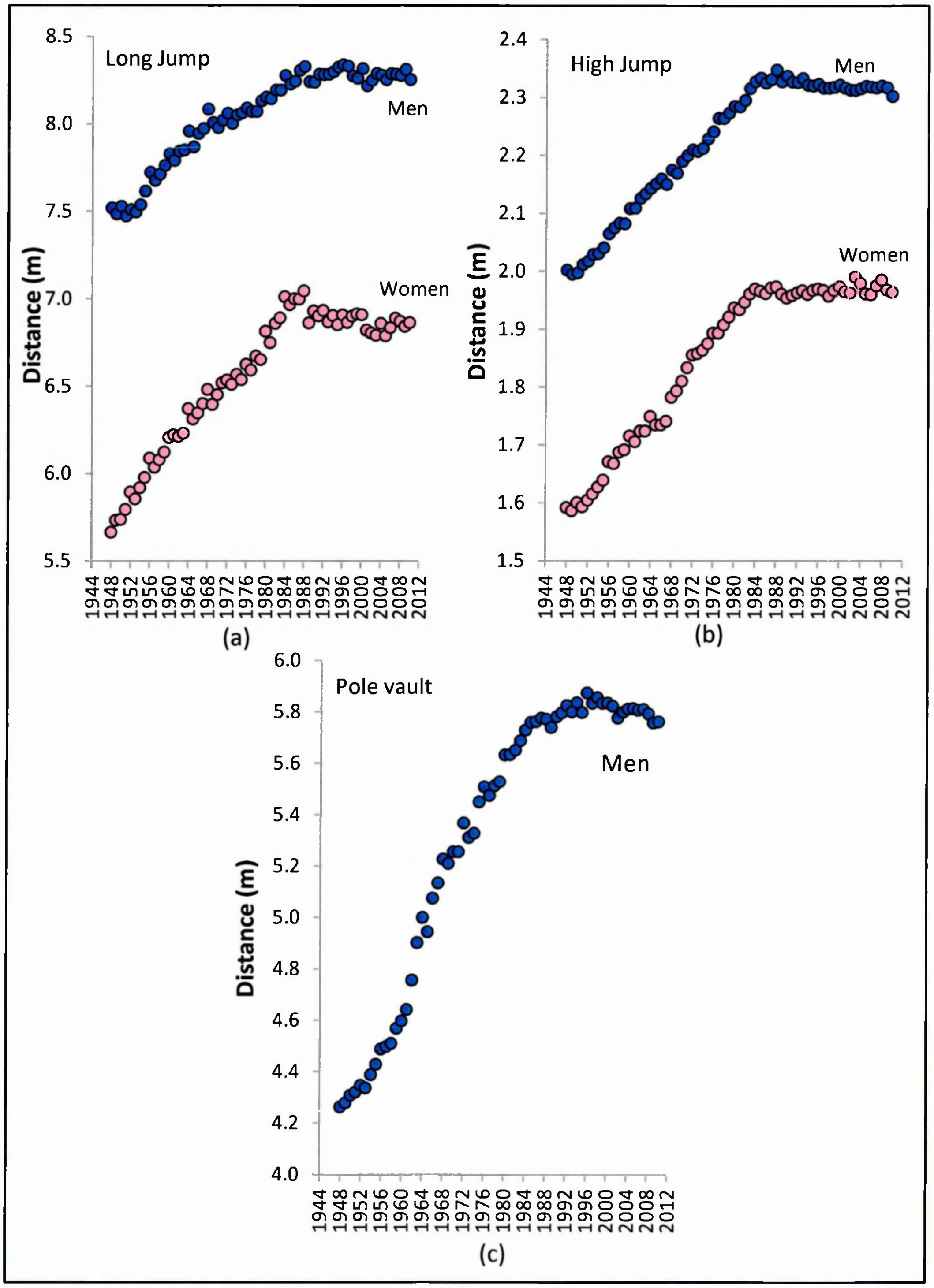


Figure 7.15: Mean of the top 25 raw performance figures in metres against historical year for the men's and women's field jumping events (a) High jump (b) Long jump and (c) Pole Vault (men only)

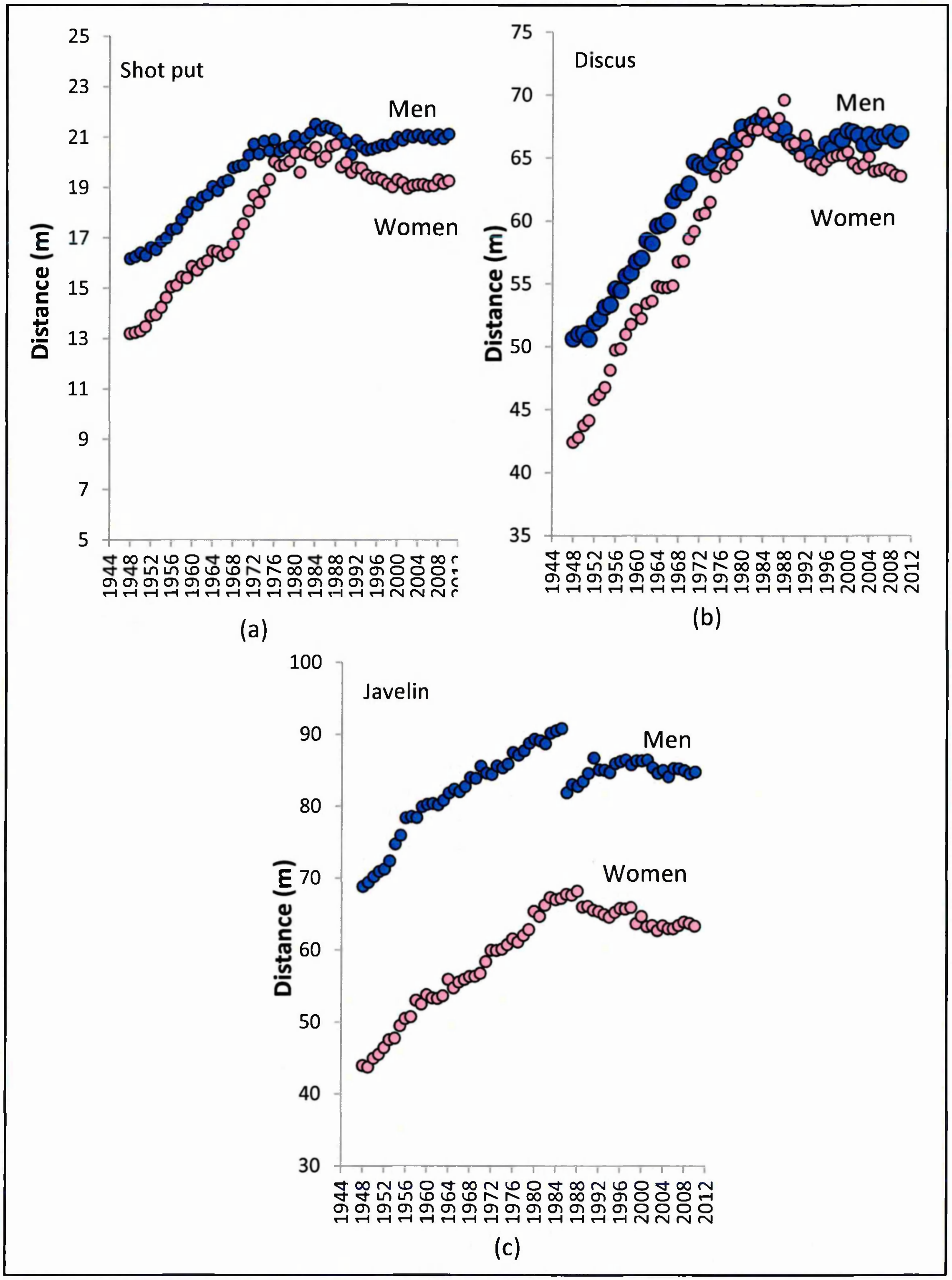


Figure 7.16: Mean of the top 25 raw performance figures in metres against historical year for the men's and women's field throwing events (a) Shot put (b) Discus and (c) Javelin

7.6.(a) Athletic field performance: Performance improvement index (1948 baseline)

Raw performance figures in all the field events have been converted in to performance improvement index values for each year from 1948. The men's throwing and jumping events are shown in Figure 7.17 (a) and (b) respectively and the women's jumping and throwing events are shown in Figure 7.18 (a) and (b) respectively.

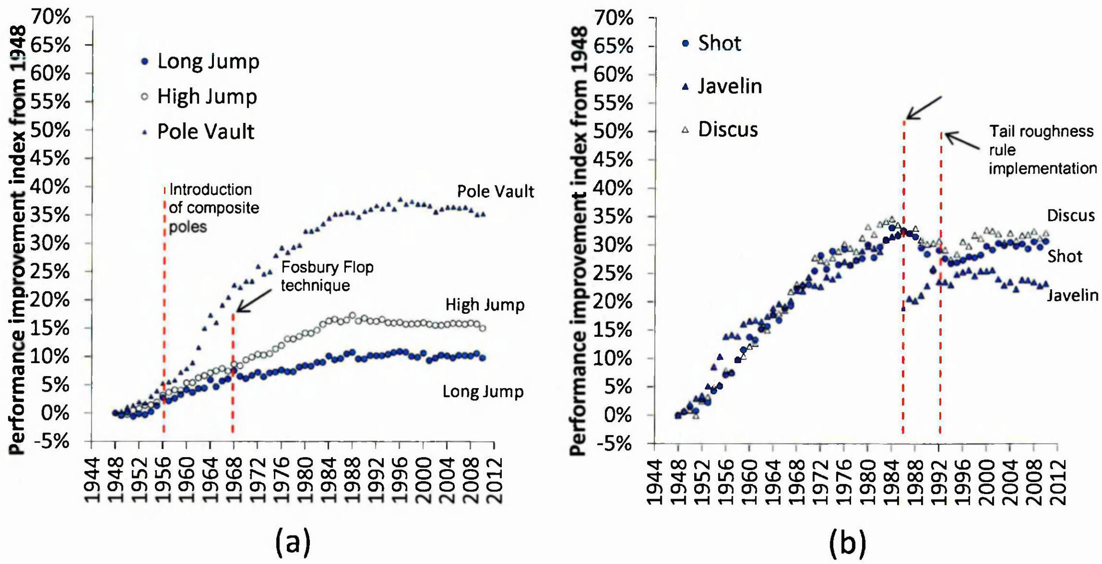


Figure 7.17: Percentage increase in performance improvement index with a baseline of 1948 against year for men's: (a) Field jumping events and (b) Field throwing events

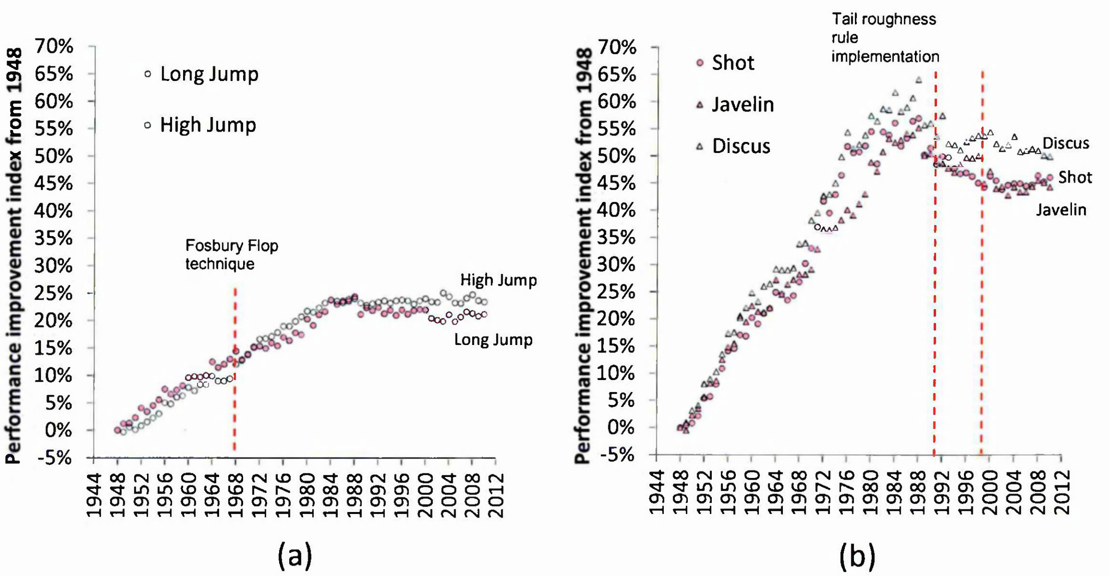


Figure 7.18: Percentage increase in performance improvement index with a baseline of 1948 against year for women's: (a) Field jumping events and (b) Field throwing events

For each field event the maximum magnitude in terms of percentage increase in the performance improvement index, and the year at which this maximum value was found, has been represented graphically in Figure 7.19.

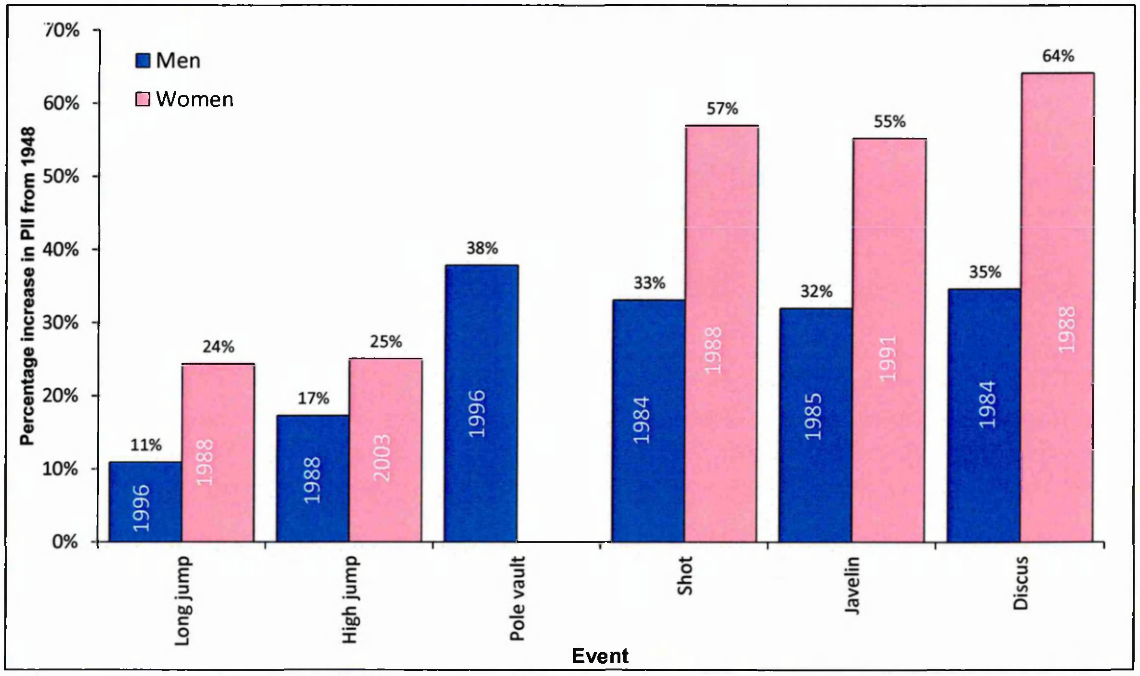


Figure 7.19: Maximum percentage increase in the performance improvement index from 1948 for all field events, shown with year of peak performance.

7.7 Discussion – Field event performance improvement

7.7.(a) General improvement

A similar general trend of improvement is seen across all field events; this trend is the same phenomenon seen in running performance improvements and takes the form of an exponential decay curve.

7.7.(b) Men versus women

As with the running events, higher levels of performance improvement can be seen for all the women's field events when compared to the men's. This again could be due to the choice of baseline performance figures, and that in 1948 females were less competitive than their male counterparts at that particular time, with reasons being a less developed training technologies and a reduced competing population.

7.7.(c) Grouping of similar indices

Field events both male and female show a range in percentage increase in the PII, however clear groups can be seen within the different events. For example the improvement across all the throwing events for males is very similar, with percentage increases ranging from 33% increase in the shot put to 35% increase in the discus. This is also the same for the jumping events and we see the female long jump and high jump improve by 24% and 25% respectively. The improvements seen in the jumping events are comparable to the improvements seen in the sprinting events; a 10% and 11% improvement is seen in both the male 100 metres and the long jump respectively. This is not surprising as the 100 metres and the long jump are similar in nature in that the maximum attainable speed of each athlete governs the overall performance.

7.7.(d) Interventions

7.7.d.(i) Performance-enhancing drugs

A large variation can be seen in the years in which peak performances were produced. The earliest year in which a peak PII occurred was in the women's 800 metres, in 1980. The rest of the female events examined also had peak PII values in the 1980s, apart from the high jump which peaked in 2003. The average year in which PII peaked in the female running events was 1985 which is similar to the average year in the field events of 1991. This pattern is similar for the men's field events with the earliest peak year being 1984 for both the shot and the discus. The pole vault was the latest men's field event to have a peak year in 1996 with the average for the entirety of male field events being 1989. As with the women's running events it is believed that the peak performances seen in all field events in the late 1980s and early 1990s was down to an external intervention, the use of performance-enhancing drugs.

The only event to see a peak performance level in the most recent decade was the women's high jump. The recent peak year could indicate that performance in the women's high jump highly influenced by performance-enhancing drugs and this event is more technique dependent rather than pure power driven which can be easily enhanced by drugs.

Within the performance improvement trends there appears to be a linear uptake characteristic commencing around the early 1970s and peaking in the late 1980s. The specific start and peak years of these uptakes varies from event to event and therefore needs to be tailored for individual events. The magnitude of this peak also seems to vary from event to event the level of this magnitude dictates the influence of drugs in each different event. A decline characteristic also seems apparent after the peak year. This trend was not found in running. The year at which the decline function ends also seems to vary from event to event. Therefore a tailored decline end year could be chosen for each event and gauged by the year where performances stop declining after a peak value and start increasing once more. The decline linear model, accounts for the uptake of new drug testing technologies and the slow eradication of performance-enhancing drugs in these field events.

7.7.d.(ii) High jump – Fosbury Flop

Within the men's high jump performance data there does not appear to be a clear step change in performance after the introduction of the "Fosbury Flop" in 1968. This is in contradiction to Balmer et al. (2012), who found that the Fosbury flop increased Olympic performance. In Balmer's study, Olympic performances (top 8 at each Olympic Games from 1948) were used so there was a period of four years between data. In Figure 7.17 yearly top 25 data points are presented which has an increased resolution of performance data compared to Balmer's study.

However, there does seem to be a slight step change in the women's high jump event in 1969 and could be the start of the adoption of the Fosbury flop in the women's event. The women's high jump event also appears to show an increase in the gradient of the performance improvement trend from the late 1960s to the mid-1970s and could be due to a linear uptake up the Fosbury Flop. Within the men's event there does appear to be a very slight linear uptake of the Fosbury Flop as the rate of change of performance improvements in this event increases slightly after 1968.

7.7.d.(iii) Pole Vault – Composite poles

The introduction of composite poles in the pole vault event in 1956 seems to have greatly influenced performances from the early-1960s onwards, with a large increase in the rate of change of performance figures during the 1960s. There does not appear to be a significant change in the rate of improvement which coincides with the introduction of metal poles in the early 1950s and so the influence of these metal poles will not be modelled. In 1972 it appears that the development and uptake of composite poles ceased and as newly developed Cata-Poles were banned from use by the IAAF in the 1972 Olympic Games (IAAF).

7.7.d.(iv) Javelin – Hollow javelin

There appears to be an increase in the gradient of performance improvements in the men's javelin event from 1953 up until 1956 and could be the result of the uptake of new hollow javelins into the event. There does not appear to be a linear uptake in the women's javelin event and this could be due to the lower mass of the women's javelin in comparison to the men's javelin.

7.7.d.(v) Javelin – rule changes

In 1986 and 1999 for the men's and women's javelin events respectively there does appear to be step a change in performance due to the introduction of the rule to move the centre of gravity forward in the javelin. The 1999 step change in the women's javelin seems to be less significant and hard to see within the possible drugs decline, but will be attempted to be modelled.

There does not appear to be a significant drop in performance with the introduction of tail roughness specification at the end of 1991, but a step change will be attempted to be modelled in both the men's and women's javelin events in 1992.

7.7.(e) Drop in 2010 – High jump and long jump men's events

In 2010 there appears to be an unexplained drop in performance in the men's long jump and high jump event. This step change does not seem to be replicated to the same degree in any other field events. It was initially thought that these steps in the men's long jump and high jump were errors in the result collection, but performance data was double checked and no errors were found. It is not fully clear why there is a clear step change only in the men's high jump and long jump, but it is likely that these drops in performance are due to the natural Olympics and World championships performance cycle. In 2010 athletes could have treated this season as a rest year before the 2011 World Championships and 2012 Olympic Games, meaning performances will have dropped. The step change in 2010 seen in the men's high jump and long jump will not be modelled with a step change, but accounted for with Olympic sine wave modelling function. One other possible reason for the drop in long jump performance could be that athletes who have traits which make them excel at the long jump also correspond to sprinting (Foster 2010). Sprinting is a far more glamorous than the long jump events so these athletes may be inclined to compete in sprinting events and move away from the long jump, thus reducing the pool of athletes and lowering performance.

7.8 Intervention that will be modelled: Predicted interventions

7.8.(a) Instantaneous step changes from global rule changes Javelin

Step change improvement functions will be used to model the instantaneous rule changes seen in the men's and women's javelin event. The years at which a step change will be implemented in the men's and women's javelin events is shown in Table 7.1.

Table 7.1: Step change intervention years used to model the instantaneous rule changes in the men's and women's javelin event

Rule change:	Year
Men's Javelin Rule change: Centre of gravity	1986
Men's Javelin Rule change: Roughness specification	1992
Women's Javelin Rule change: Centre of gravity	1999
Women's Javelin Rule change: Roughness specification	1992

7.8.(b) Linear technology uptakes

Technologies introduced in the field events do not conform to a step change function, but are more accurately modelled using a linear uptake function. The start and end years of the technology uptake functions for the different technologies are shown in Table 7.2. The start year of the linear uptake is the year the technology was introduced and found through historical sources. The end year of the linear uptake function is the year at which the gradient of improvement function returns to its original level prior to the introduction of the technology.

Table 7.2: Start and end years of the linear technology uptake function used to model the various technologies introduced to field events since 1948.

Technology	Start year	End year
High jump Fosbury Flop	1968	1976
Pole vault - composite materials	1956	1972
Hollow Javelins	1953	1956

7.8.(c) Performance-enhancing drugs, tests, uptake and decline

As with running events the step changes due to the improvements in drug testing procedures will be modelled with a step change improvement function using intervention years of 1989 and 2000. In addition to this an uptake and decline function will be used to model the technology uptake of performance-enhancing drugs and subsequent uptake of better drug testing technologies. The start year of the linear uptake of the use of performance-enhancing drugs will be set at 1968 as with the procedure for running event.

The peak year of the linear uptake will be the denoted by the peak year prior to 2000 of performances and these years are displayed in Figure 6.10. The end of performance decline year will be denoted by the year prior to an increase in performances once the decline has ended. The years that will be used in the drugs uptake and decline function are summarised in Table 7.3.

Table 7.3: Start, peak and end years of the linear uptake and decline function used to model the uptake of performance-enhancing drugs and subsequent uptake of better drug testing procedures

Event	Start year	Peak year (Drugs period pre 2000)	End year of decline
Long jump Men	1968	1996	2001
Long jump Women	1968	1988	2003
High Jump Men	1968	1988	2002
High Jump Women	1968	1988	1990
Pole Vault Men	1968	1996	2002
Shot put Men	1968	1984	1994
Shot put Women	1968	1988	2003
Discus Men	1968	1984	1994
Discus Women	1968	1988	1993
Javelin Men	1968	1996	2005
Javelin Women	1968	1988	2001

7.9 Improvement function generation steps

The improvement function generation steps are now laid out in the following tables. Table 7.4 shows the improvement function generation steps for field events with no technology interventions other than the believed drug influence. These events are the men's and women's long jump, discus and the shot put. Table 7.5 now shows the fitting procedure for field events with one believed addition technology linear uptake in addition to drugs. These events are the men's and women's high jump and men's pole vault. Finally Table 7.6 shows the fitting procedure for the men's and women's javelin which is believed to contain technology influence two step changes due to rule changes in the javelin specification, a linear uptake of technology and finally drug influence. As explain previously two drug linear uptakes with different start years were trialled. The start year of the linear uptake that gives the best goodness of fit value was used for the rest of the fitting procedure.

Table 7.4: Improvement function generation steps for the men's and women's long jump, discus and shot put with low technology influence

Step no.	**Intervention modelled:**	**Model description:**
1	Global improvement	Global improvement trend
2	Drug testing step change 1989	Step change 1989
3	Drug testing step change 2000	Step change 2000
4	Drugs linear uptake 2	Expo + Drugs uptake 1968-Peak year and step change
5	Drugs linear uptake and decline (best start date)	Drugs up and decline 1968– Peak year – Decline year
6	Drugs linear uptake and decline and Olympics	Periodic function of four years from 1948

Table 7.5: Improvement function generation steps for the men's and women's high jump and pole vault (pole vault men only) with a linear technology uptake

Step no.	**Intervention modelled:**	**Model description:**
1	Global improvement	Global improvement trend
2	Linear uptake of technology	Linear uptake
3	Drug testing step change 1989	Step change 1989
4	Drug testing step change 2000	Step change 2000
5	Drugs linear uptake 2	Expo + Drugs uptake 1968-Peak year and step change
6	Drugs linear uptake and decline (best start date)	Drugs up and decline 1968– Peak year – Decline end year
7	Drugs linear uptake and decline and Olympics	Periodic function of four years from 1948

Table 7.6: Improvement function generation steps for the men's and women's javelin with a linear technology uptake and two additional step changes for rule changes concerning the javelin

Step no.	Intervention modelled:	Model description:
1	Global improvement	Global improvement trend
2	Javelin specification change COM	Step change (men: 1986, women: 1999)
3	Javelin specification change tail roughness	Step change 1991
4	Linear uptake of technology: Hollow javelin's	Linear uptake (1953-1956)
5	Drug testing step change 1989	Step change 1989 (3 ints)
6	Drug testing step change 2000	Step change 2000 (4 ints)
7	Drugs linear uptake 2	Expo + Drugs uptake 1968-Peak year and step change (3ints)
8	Drugs linear uptake and decline (best start date)	Drugs up and decline 1968 – Peak year – Decline end year (4 ints)
9	Drugs linear uptake and decline and Olympics	Periodic function of four years from 1948 (4 ints)

7.10 Results – graphical representation and goodness of fit

The change in the goodness of fit values (adjusted regression coefficient) for the first improvement function generation fitting procedure (field events with no additional technology interventions other than drugs) has been plotted against the fitting step and shown in Figure 7.20. The same again for the second fitting procedure (field events with one additional technology linear uptake) has been plotted in Figure 7.21. Finally in Figure 7.22 the change in goodness of fit values for the fitting procedure for the men's and women's javelin containing two additional step change interventions due to rule changes have been plotted for each fitting step.

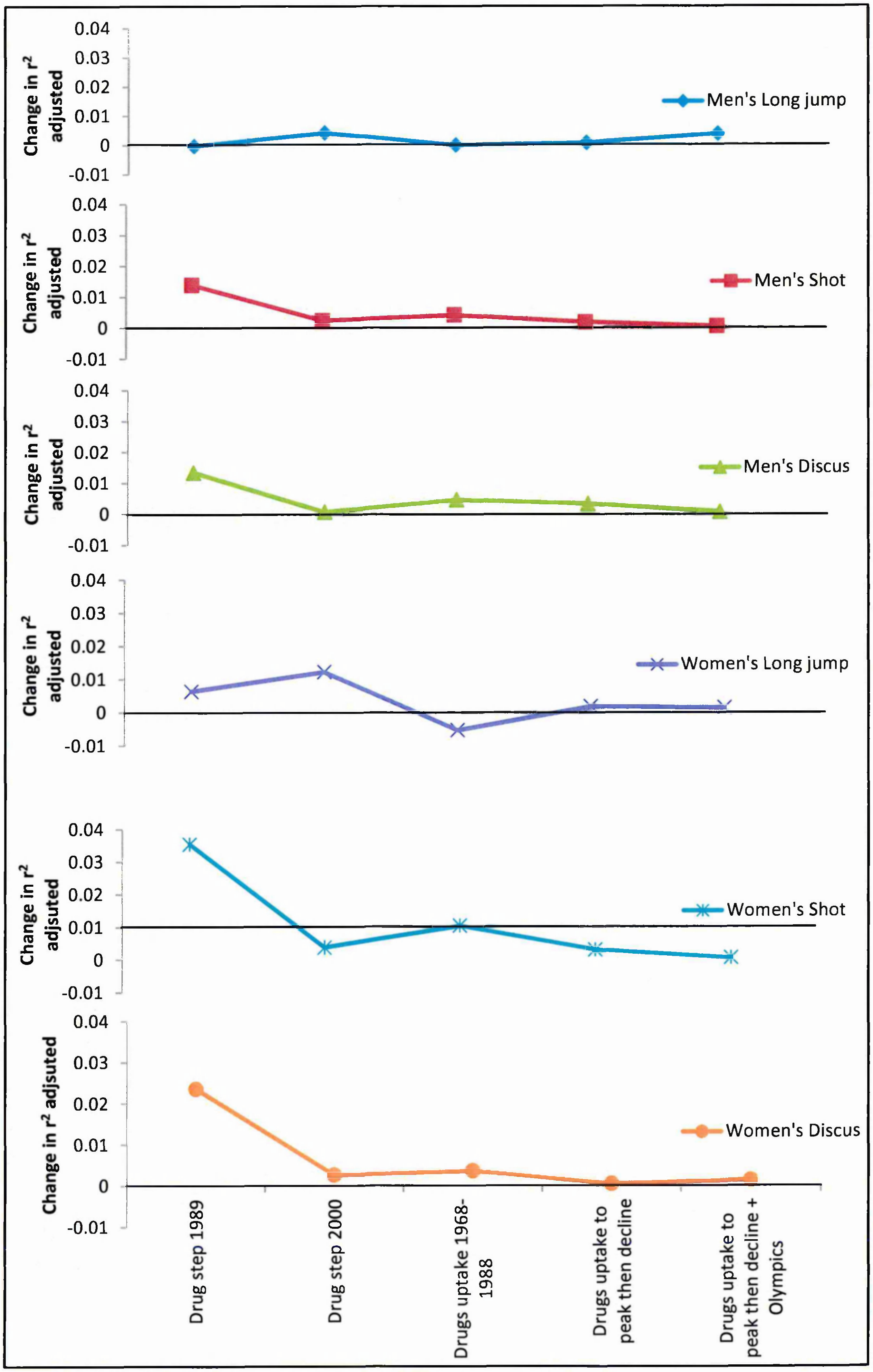


Figure 7.20: Change in adjusted regression coefficient for the modelling steps men's and women's long jump, shot put and discus

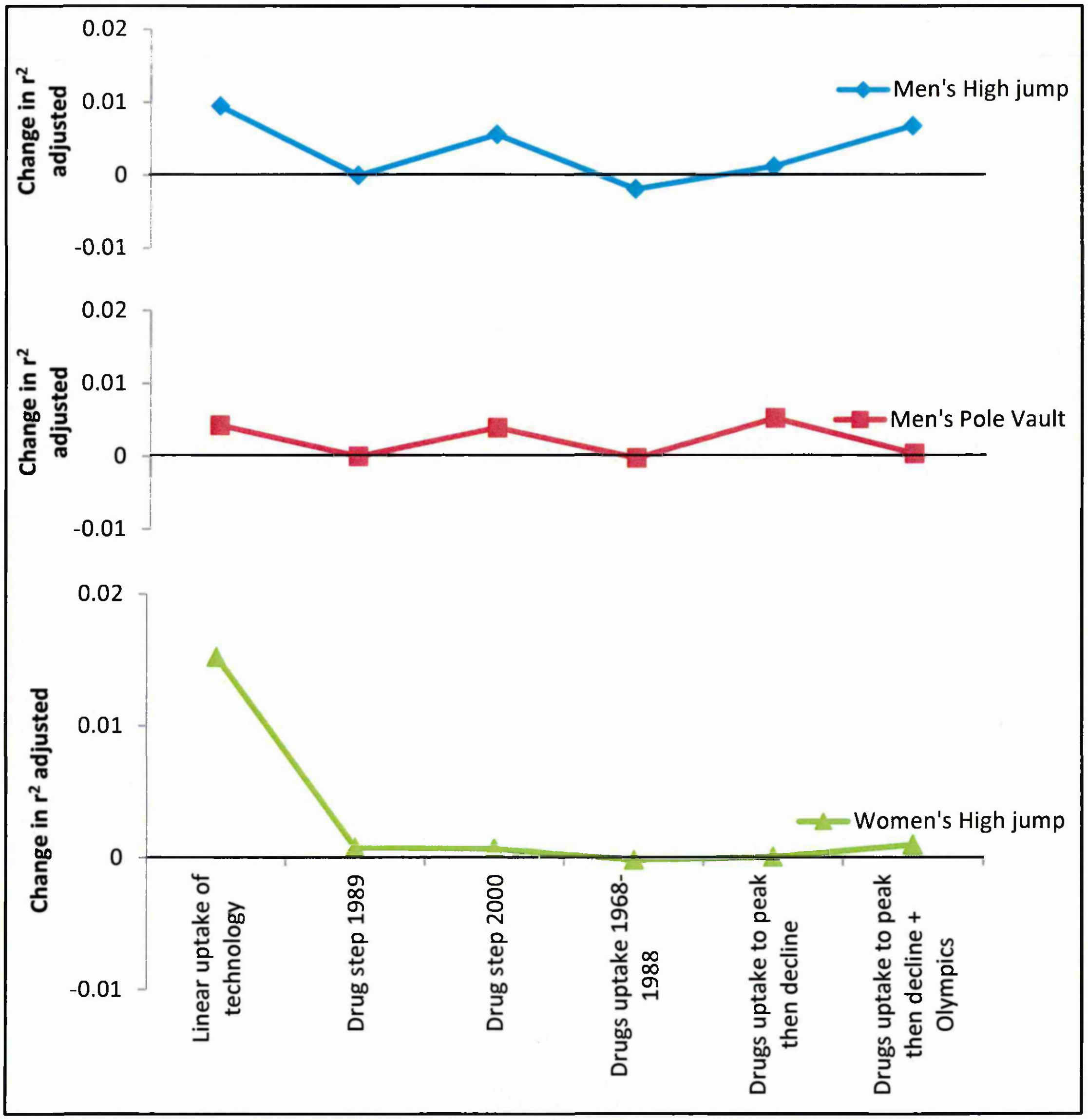


Figure 7.21: Change in adjusted regression coefficient for the modelling steps men's and women's high jump and men's pole vault

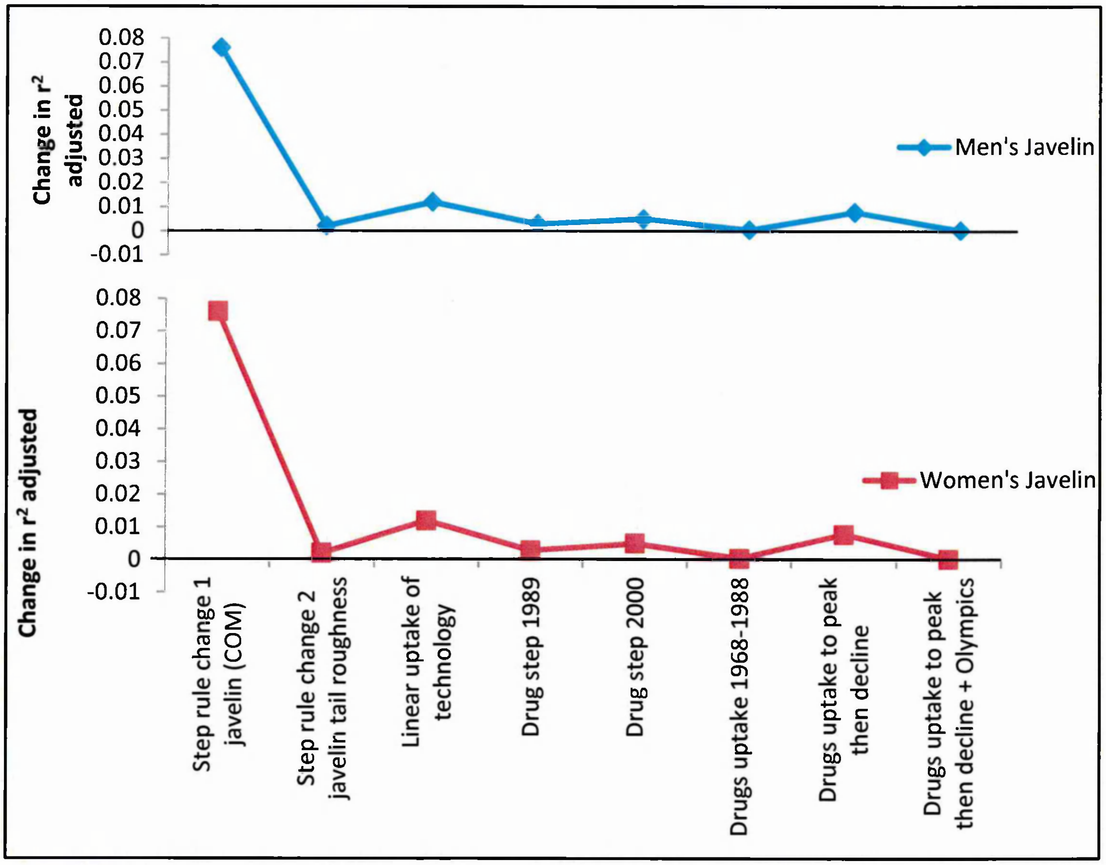


Figure 7.22: Change in adjusted regression coefficient for the modelling steps men's and women's javelin event jump and men's pole vault

Any unexpected parameter values found during the fitting procedure for all field events have been noted and displayed in Table 6.6. It appears that no men's field events saw a step change in 2000 and could be because all improvement due to the use of performance-enhancing drugs were eliminated prior to the formation of WADA. In addition to this the modelling function did not work correctly when attempting to fit a step change in 1989 for some events as the drug testing influence was found to be more than the drug influence peak.

Table 7.7: Interventions for the different events that have been excluded from the final improvement function model as unexpected parameters were found

Event	Modelling step/ intervention	Reason for omitting from final model
Men's Javelin and Shot put Women's high jump	Drugs step 1989	Positive effect found
All men's field events, and women's shot put and javelin	Drug step change 2000	Positive effect found
Men's discus and women's shot put	Drugs step change 1989	Effect greater than drugs peak
Men's high jump	Linear uptake of the Fosbury flop	Negative uptake gradient found

Taking in to consideration which modelling steps improve the goodness of fit of the improvement function and any unexpected parameter found, the final improvement functions for each field event have been described in Table 6.7 accompanied with the GUI improvement function number.

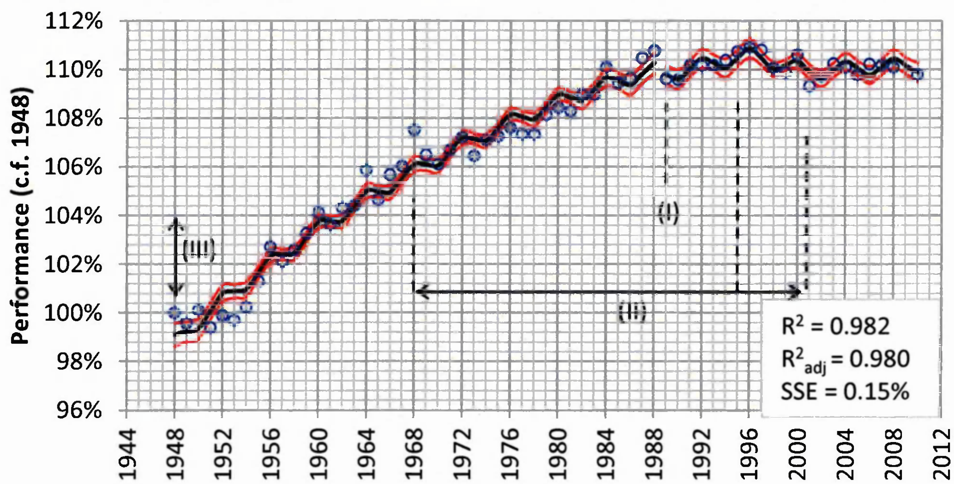
Table 7.8: Final improvement function model and GUI assigned model number, customised for each event

Event	Model description	Model type
Long jump - men	Drugs uptake and decline + Olympics + testing 1989 step change	Exp + 1 step + drugs up and down + Olympics
Long jump - women	Drugs uptake and decline + testing 1989/2000 step change + Olympics	Exp + 2 steps + drugs up and down + Olympics
High jump - men	Drugs uptake and decline + Olympics	Exp + drugs up and down + Olympics
High jump - women	Linear technology uptake (1968-1976) + custom drugs uptake and decline + testing 2000 step change + Olympics	Exp + lin uptake +1 step + drugs up and down + Olympics
Pole vault - men	Linear technology uptake (1956 – 1972) + drugs uptake and decline + Olympics + Testing 1989 step change and	Exp + lin uptake +1 step + drugs up and down + Olympics
Shot – men	Drugs uptake and decline + Olympics	Exp + drugs up and down + Olympics
Shot – women	Drugs uptake and decline + Olympics	Exp + drugs up and down + Olympics
Discus – men	Drugs uptake and decline + Olympics	Exp + drugs up and down + Olympics
Discus – women	Drugs uptake and decline + testing 1989/2000 step change + Olympics	Exp + 2 steps + drugs up and down + Olympics
Javelin- men	Javelin rule changes 1986/1992 + linear technology uptake (1953-1956) + drugs uptake and decline + Olympics	Exp + lin uptake +2 steps + drugs up and down + Olympics
Javelin - women	Javelin rule changes 1999/1992 + linear technology uptake (1953-1956) + drugs uptake and decline and testing 1989 + Olympics	Exp + lin uptake +3 steps + drugs up and down + Olympics

7.11 Final improvement models – field events

The final improvement functions models for all the field events examined have been represented graphically from Figure 7.23 to Figure 7.33. Each intervention accounted for within the final improvement function has also been labelled and the size of the different parameters summarised.

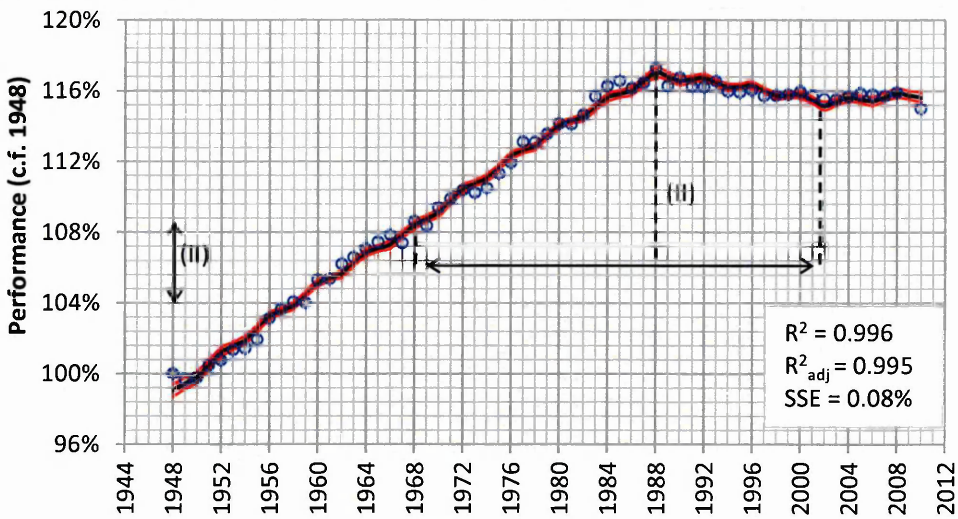
Men's long jump



	Intervention	Parameters
	Global improvement	L=110.67% (± 0.97); a=0.1613 (± 0.05); b=5.7185 (± 1.37)
I	Stricter drug testing	k_1=99.69% (± 0.63); $k_1 year$=1989
II	Drugs uptake and down turn	D=0.03%yr^{-1}(± 0.02); D_{peak}=0.94% (± 0.48); DD=-0.19%yr^{-1}; D_{start}=1968; D_{end}=1996; DD_{end}=2001
III	Olympic Games	Amp, A=0.31% (± 0.18)
		R^2=0.982; R^2_{adj}=0.980; MSE =0.003%; SSE=0.15%

Figure 7.23: Final improvement function model for the men's long jump event

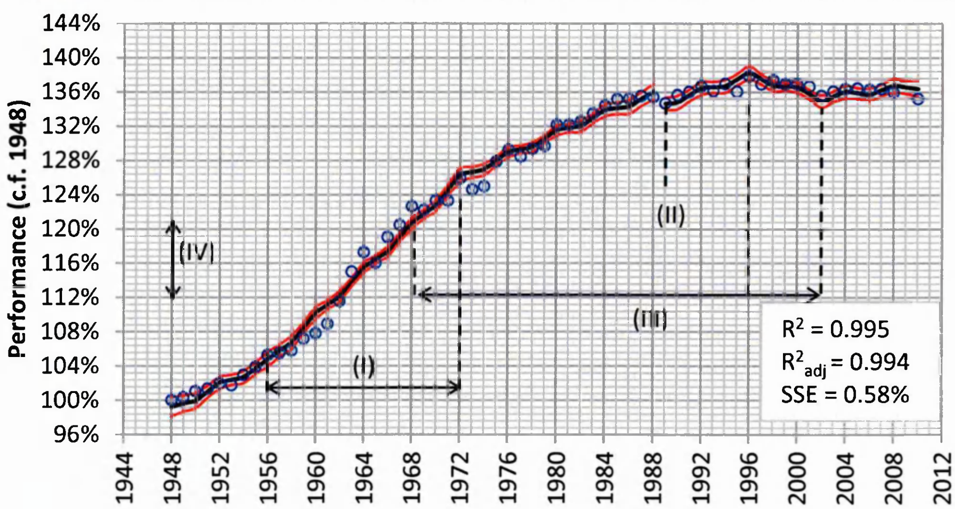
Men's high jump



	Intervention	Parameters
	Global improvement	L=116.24% (± 1.17); a=0.1165 (± 0.02); b=6.2438 (± 0.64)
I	Drugs uptake and down turn	D=0.16%yr^{-1}(± 0.02); D$_{peak}$=3.27% (± 0.39); DD=-0.23%yr^{-1}; D$_{start}$=1968; D$_{end}$=1988; DD$_{end}$=2002
II	Olympic Games	Amp, A=0.17% (± 0.14)
		R^2=0.996; R^2_{adj}=0.995; MSE =0.001%; SSE=0.08%

Figure 7.24: Final improvement function model for the men's high jump event

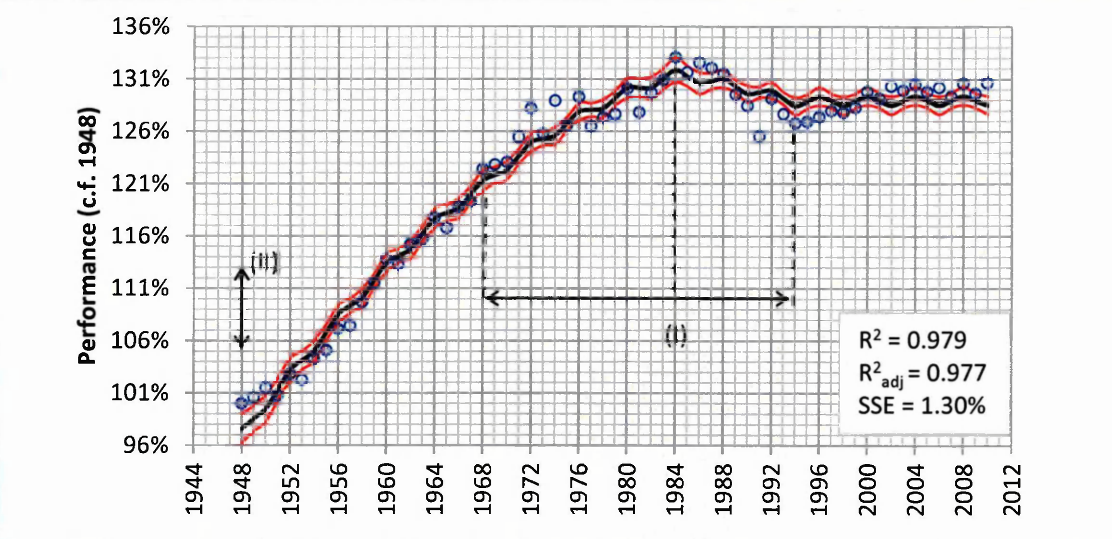
Men's pole vault



	Intervention	Parameters
	Global improvement	L=128.06% (± 3.64); a=0.0674 (± 0.05); b=6.9905 (± 3.34)
I	Uptake of composite poles	LU=0.69%yr^{-1}(±0.36); LU$_{peak}$=11.07% (± 3.21); LU$_{start}$=1956 ; LU$_{end}$=1972
II	Stricter drug testing	k_1=98.40% (± 1.38); $k_1 year$=1989
III	Drugs uptake and down turn	D=0.15%yr^{-1}(± 0.04); D_{peak}=4.12% (± 1.23); DD=-0.69%yr^{-1}; D_{start}=1968; D_{end}=1996; DD_{end}=2002
IV	Olympic Games	Amp, A=0.32% (± 0.35);
		R^2=0.995; R^2_{adj}=0.994; MSE =0.01%; SSE=0.58%

Figure 7.25: Final improvement function model for the men's pole vault event

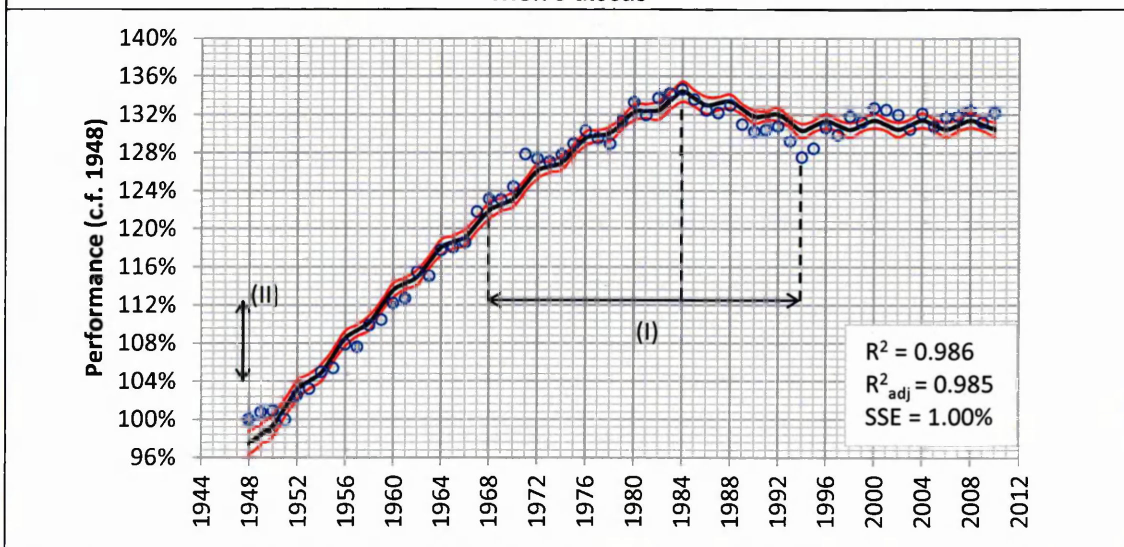
Men's shot put



	Intervention	Parameters
	Global improvement	L=128.98% (±2.97); a=0.0034 (±0.002); b=50.5965 (± 8.50)
I	Drugs uptake and down turn	D=0.21%yr^{-1}(± 0.09); D_{peak}=3.38% (± 1.40); DD=-0.34%yr^{-1}; D_{start}=1968 ; D_{end}=1984; DD_{end}=1994
II	Olympic Games	Amp, A=0.45% (± 0.54)
		R^2=0.979; R^2_{adj}=0.977; MSE =0.02%; SSE=1.30%

Figure 7.26: Final improvement function model for the men's shot put event

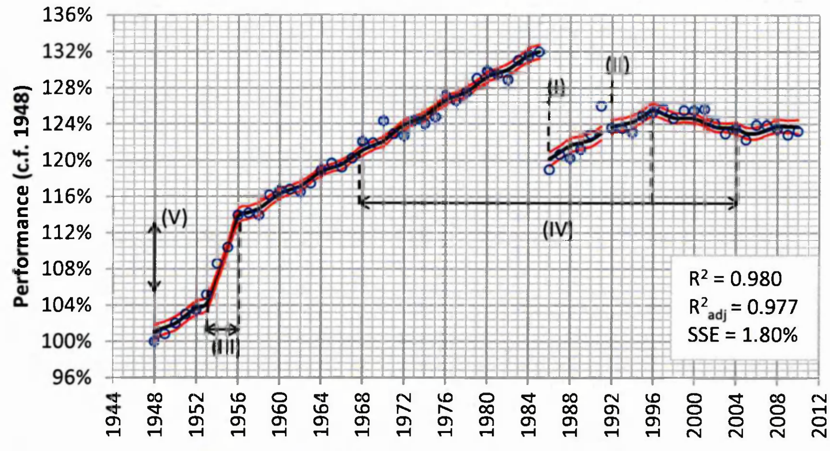
Men's discus



	Intervention	Parameters
	Global improvement	L=130.95% (± 0.61); a=0.0034 (± 0.001); b=49.0811 (± 13.23)
I	Drugs uptake and down turn	D=0.27%yr^{-1} (± 0.08); D_{peak}=4.24% (± 1.26); DD=-0.42%yr^{-1}; D_{start}=1968; D_{end}=1984; DD_{end}=1994
II	Olympic Games	Amp, A=0.48% (± 0.47)
		R^2=0.986; R^2_{adj}=0.985; MSE =0.02%; SSE=1.00%

Figure 7.27: Final improvement function model for the men's discus event

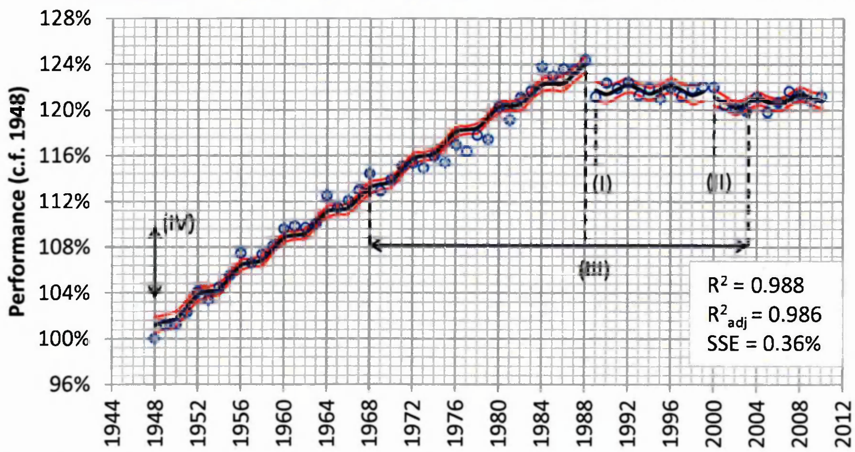
Men's javelin



	Intervention	Parameters
	Global improvement	L=130.84% (± 4.02); a=0.0765 (± 0.04); b=16.4373 (± 2.35)
I	COM rule change	k_1=87.81% (± 1.29); k_1year=1986
II	Tail roughness rule change	k_2=99.996% (± 1.20); k_2year=1992
III	Uptake of hollow javelins	LU=2.49%yr^{-1}(± 0.50); LU_{peak}=7.46% (± 1.49); LU_{start}=1953 ; LU_{end}=1956
IV	Drugs uptake and down turn	D=0.16%yr^{-1}(± 0.05); D_{peak}=4.53% (± 1.46); DD=-0.50%yr^{-1}; D_{start}=1968 ; D_{end}=1996; DD_{end}=2005
V	Olympic Games	Amp, A=0.20% (± 0.31)
	COM rule change	R^2=0.989; R^2_{adj}=0.987; MSE =0.007%; SSE=0.41%

Figure 7.28: Final improvement function model for the men's javelin event

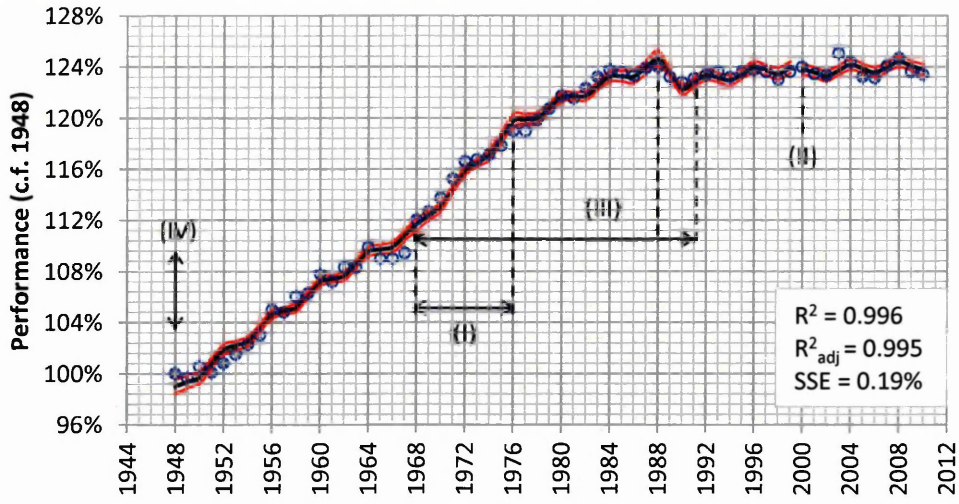
Women's long jump



	Intervention	Parameters
	Global improvement	L=124.65% (± 3.21); a=0.0752 (±0.02); b=7.3257 (± 1.78)
I	Stricter drug testing	k_1=98.07% (± 1.15); k_1year=1989
II	Formation of WADA	k_2=99.18% (± 1.42); k_2year=2000
III	Drugs uptake and down turn	D=0.15%yr^{-1} (± 0.06); D_{peak}=3.12% (± 1.25); DD=-0.21%yr^{-1}; D_{start}=1968; D_{end}=1988; DD_{end}=2003
IV	Olympic Games	Amp, A=0.38% (± 0.29)
		R^2=0.988; R^2_{adj}=0.986; MSE =0.006%; SSE=0.36%

Figure 7.29: Final improvement function model for the women's long jump event

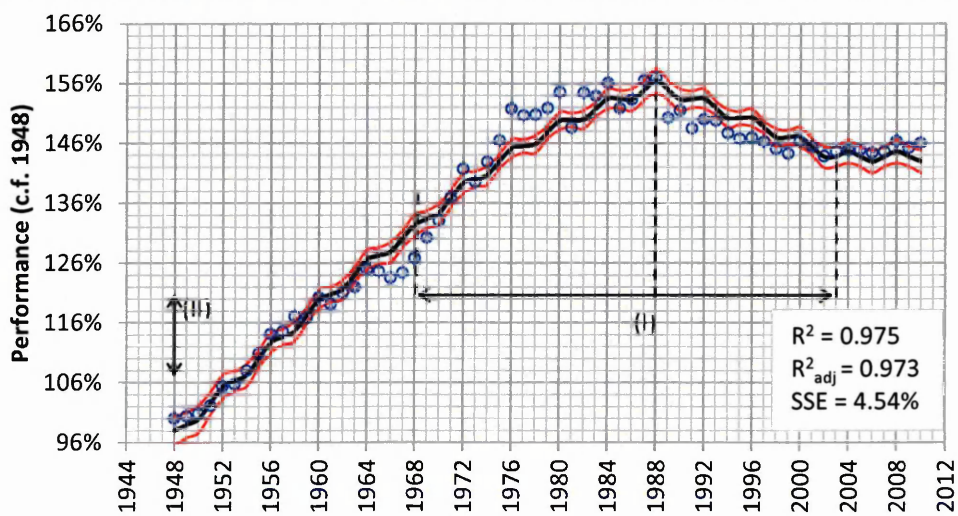
Women's high jump



	Intervention	Parameters
	Global improvement	L=121.33% (± 1.74); a=0.05730 (± 0.01); b=9.0087 (± 1.37)
I	Uptake of Fosbury flop technique	$LU=0.46\%yr^{-1}$ (± 0.15); LU_{peak}=3.69% (± 1.16); LU_{start}=1968 ; LU_{end}=1976
II	Formation of WADA	k_1=99.42% (± 0.67); k_1year=2000
III	Drugs uptake and down turn	$D=0.10\%yr^{-1}$(± 0.04); D_{peak}=2.09% (±0.82); DD=-1.05%yr^{-1}; D_{start}=1968; D_{end}=1988; DD_{end}=1990
IV	Olympic Games	Amp, A=0.37% (± 0.21)
		R^2=0.996; R^2_{adj}=0.995; MSE =0.003%; SSE=0.19%

Figure 7.30: Final improvement function model for the women's high jump event

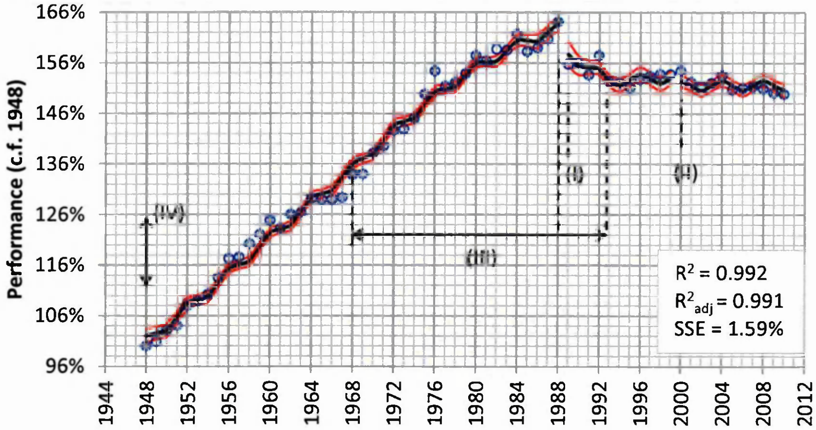
Women's shot put



	Intervention	Parameters
	Global improvement	L=143.80% (± 1.63); a=0.000434 (±0.0003); b=155.5112 (± 75.77)
I	Drugs uptake and down turn	$D=0.61\%yr^{-1}$ (± 0.14); D_{peak}=12.13% (±2.70); DD=-0.81%yr^{-1}; D_{start}=1968; D_{end}=1988; DD_{end}=2003
II	Olympic Games	Amp, A=0.86% (± 1.00)
		R^2=0.975; R^2_{adj}=0.973; MSE =0.08%; SSE=4.54%

Figure 7.31: Final improvement function model for the women's shot put event

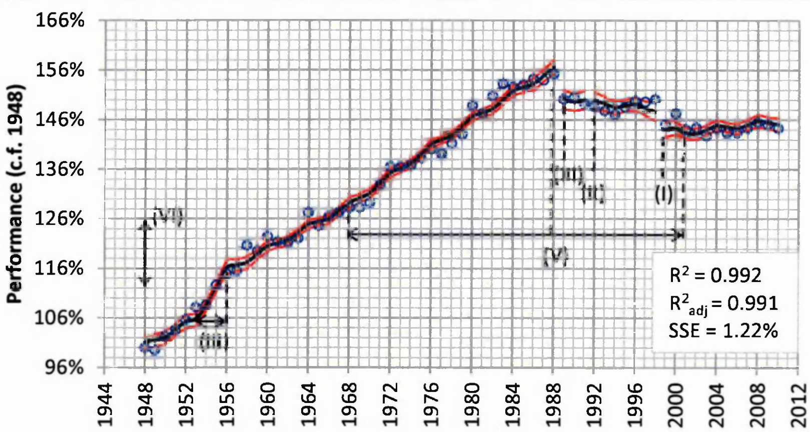
Women's discus



	Intervention	Parameters
	Global improvement	L=157.17% (± 3.97); a=0.000467 (± 0.0002); b=122.8647 (± 31.58)
I	Stricter drug testing	k_1=96.00% (± 3.29); k_1year=1989
II	Formation of WADA	k_2=98.47% (± 1.68); k_2year=2000
III	Drugs uptake and down turn	D=0.39%yr^{-1} (± 0.15); D_{peak}=7.71% (± 3.05); DD=-1.54%yr^{-1}; D_{start}=1968; D_{end}=1988; DD_{end}=1993
IV	Olympic Games	Amp, A=0.97% (± 0.60);
		R^2=0.992; R^2_{adj}=0.991; MSE =0.03%; SSE=1.59%

Figure 7.32: Final improvement function model for the women's discus event

Women's javelin



	Intervention	Parameters
	Global improvement	L=150.33% (± 6.14); a=0.008323 (± 0.005); b=19.8715 (± 7.41)
I	COM rule change	k_3=96.31% (± 4.13); k_2year=1999
II	Tail roughness rule change	k_2=99.47% (± 2.96); k_1year=1992
III	Uptake of hollow javelins	LU=2.17%yr^{-1} (± 0.76); LU_{peak}=6.51% (± 2.31); LU_{start}=1953 ; LU_{end}=1956
IV	Stricter drug testing	k_1=94.10% (± 2.30); k_1year=1989
V	Drugs uptake and down turn	D=0.46%yr^{-1} (±0.19); D_{peak}=9.30% (± 3.76); DD=-0.71%yr^{-1}; D_{start}=1968; D_{end}=1988; DD_{end}=2001
VI	Olympic Games	Amp, A=0.52 (± 0.54)%
		R^2=0.992; R^2_{adj}=0.991; MSE =0.02%; SSE=1.22%

Figure 7.33: Final improvement function model for the women's javelin event

7.12 Results - Interventions modelled

7.12.(a) Performance-enhancing drugs uptake and decline

7.12.a.(i) Results – drug uptake and decline

It was decided to start by examining the effect of drugs in field athletic events as it appeared that an effect was found in all events. Unlike all running events, all field events were found to contain a linear uptake and decline of performance due to a drug uptake and then subsequent uptake of better drug testing procedures. Therefore this type of improvement function was used to model the influence of drugs in all field events.

The years at which the drugs uptake and decline function starts, peaks and ends as well as the peak influence of the function is shown for all field events in Table 7.9 and represented graphically Figure 7.34.

Table 7.9: The years of the uptake and decline and the peak size of the influence performance-enhancing drugs has in all the field events examined

Gender	Event	Start year	Peak year	End of decline year	Drugs peak PII %)	+/-	Drugs peak (m)	+/-
Men	Long jump	1968	1995	2001	0.94%	0.48%	0.11	0.05
	High jump	1968	1988	2002	3.27%	0.39%	0.07	0.01
	Pole vault	1968	1996	2002	4.12%	1.23%	0.18	0.05
	Shot put	1968	1984	1994	3.38%	1.40%	0.55	0.23
	Discus	1968	1984	1994	4.24%	1.26%	2.15	0.64
	Javelin	1968	1996	2005	4.53%	1.46%	3.12	1.00
Women	Long jump	1968	1988	2003	3.79%	0.94%	0.21	0.05
	High jump	1968	1988	1990	1.83%	1.13%	0.03	0.02
	Shot put	1968	1988	2003	12.13%	2.70%	1.60	0.36
	Discus	1968	1988	1993	7.71%	3.05%	3.27	1.29
	Javelin	1968	1988	2001	9.30%	3.76%	4.09	1.65

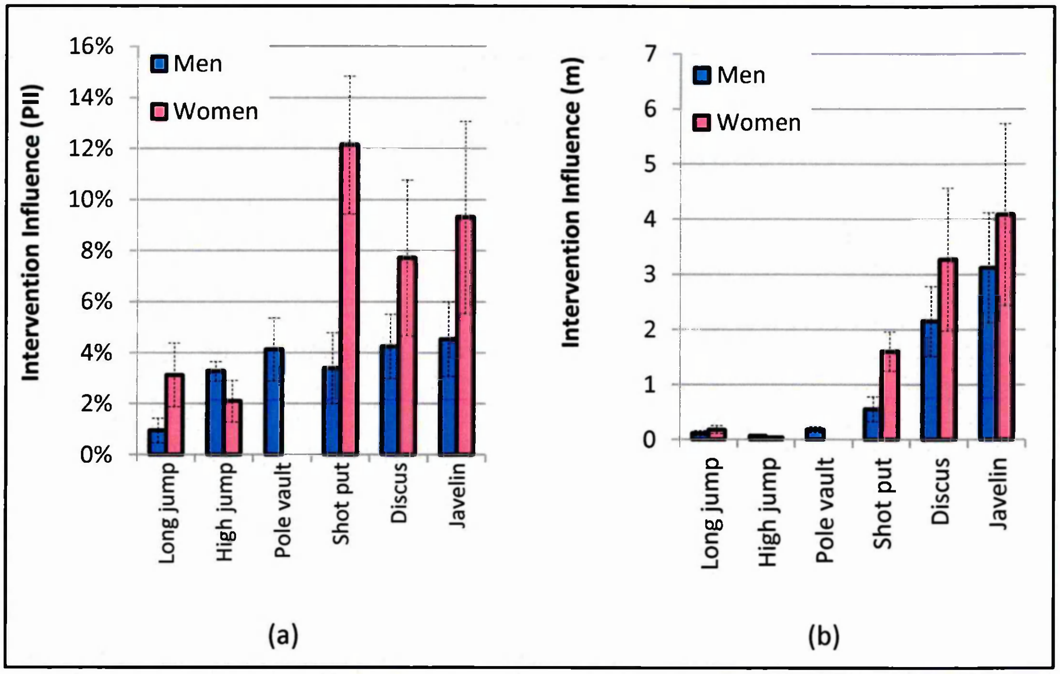


Figure 7.34: The size of the influence, the uptake and decline of performance-enhancing drug use had on all field events shown in units of (a) PII and (b) raw height gained in metres

7.12.a.(ii) Discussion – drug uptake and decline

Years of influence

Peak years

The peak year used as part of the linear uptake function appears to be the same for all women's event, with the end of the linear uptake function found to be in 1988. However, men's events see a slight variation in the peak year with some events peaking in 1984 like the shot put and discus, and some events like the javelin, long jump and pole vault peaking in the mid-1990s. The events which peaked later due to performance-enhancing drugs could be because the athletes that compete in these field events are usually older and compete at the top level for longer periods of time. This means that they could have retained some of the performance-enhancing drug desirable effects long after they stopped using them.

Linear decline all field events

As the influence of performance-enhancing drugs in field event athletes is believed to linger longer this could explain the linear decline after the introduction of better drug testing technology which was not seen in running any events. The linear decline was not seen in running events as the effect of performance-enhancing drugs in running may not be as long lasting. The period of time that running athletes can perform at their peak is shorter in comparison to a field athlete. Usually elite field event athletes are older than elite runners (Schulz & Curnow 1988). This could mean that drugs effects seen in a previous top performing cohort of runners may not be carried across a drug testing intervention where a runner retires and does compete after a drug testing intervention. Older field event athletes may continue to compete long after the 1989 drug testing intervention and residual effects of performance-enhancing drugs may be apparent. In that sense the linear decline for function is not measuring the uptake of better drug testing technologies, but could be measuring the decline in performance and time taken for performance-enhancing drugs to be eradicated from field athlete's bodily systems or the time it takes for field events to retire from elite competition.

Another reason for the linear decline could be the uptake of better drug testing procedures which slowly eliminates the use of drugs over a period of time and the linear decline function is a measure of effectiveness of the uptake of drug testing procedures.

Greatest effect

The most profound influence from the drugs uptake and decline function was found in the women's shot put event at 12.13 (+/-2.70) % improvement or + 1.60 (+/-0.36) metres. This is similar to the women's discus of 7.71 (+/-3.05) % or + 3.27 (+/-1.29) metres improvement. The percentage increase in performance figures are larger than the women's running events with an average increase of 6.53 % in field events, compared to a 3.23 % increase in performance in women's running events.

It appears that as with running events improvements in performance due to drugs were lower within men's events when compared to women's events. The greatest men's field event to be influenced by drugs was the men's javelin at 4.53 (+/-1.46) %, 3.12 (+/-1.00) metres. This is approximately 3 % lower than the maximum influence women's field event. The men's field event performance is on average influenced 3.42 % by drugs, approximately 3.11 % lower than the average for women's drug influence in field events. If differences in drug performance improvements between men's and women's performance is constant than the carrying this value across to men's running events would mean men's running events would see an improvement in performance due to drugs in the order of 0.1 % which is difficult to gauge and decipher within the overall improvement trends.

7.12.a.(iii) Conclusion – drug uptake and decline

Performance-enhancing drugs have evidently influenced field events a great deal, with the greatest influence found in women's events. The men's field events also see a significant influence from drugs, but on average this influence is lower than the women's events. On average the influence from drugs in field events is higher than running events. A major cause of this could be the nature of field throwing events, with performances driven by raw athlete power of strength. Jumping field events follow a similar pattern to running events where performance improvements from drugs are lower and at a similar level.

The peak year of the linear function to account for the uptake of performance-enhancing drugs are the same for women's events but slightly vary for men's event. The reason for this is believed to be down to the variation in the age of elite athletes and the events which peak later contain older of competing athletes which means they may see residual effects of performance-enhancing drug use.

Declines in performance are most likely down to the uptake of better drug testing procedures as well as the elimination of performance-enhancing drugs from existing athletes after the introduction of better drug testing technologies.

7.12.(b) Performance step changes due to drug testing technology introduction

7.12.b.(i) Results –drug testing technology

Shown in Table 7.10 are the magnitudes of the step change declines in performances in the field events due to the introduction of out of season random drug testing in 1989. Again in Table 7.11 are the step change declines in performance in field events due to the formation of WADA in 1999 and a step change in performance modelled in 2000. The magnitudes of the step changes have been represented graphically in Figure 7.35 and Figure 7.36 for the 1989 and 2000 step change respectively. Not all events saw an improvement in fit of the improvement function with these step changes to account for instantaneous drug testing interventions and these have been omitted from these tables. Events were also omitted when any unexpected positive step change parameters were found for the introduction of drug testing procedures. Finally events where the step change parameter was greater than the drugs peak influence

Table 7.10: The size of the influence, of the introduction of random out of competition drug testing in 1989 for all field events where an effect could be seen

Gender	Event	Intervention size (PII %)	+/-	Intervention size (m)	+/-
Men	Long jump	-0.31%	0.63%	-0.01	0.06
	High jump	-2.18%	1.39%	-0.09	0.06
	Pole vault	-1.93%	1.15%	-0.11	0.07
Women	Long jump	-4.00%	3.29%	-1.70	1.39
	High jump	-0.07%	0.82%	-0.01	0.06
	Discus	-2.18%	1.39%	-0.09	0.06
	Javelin	-5.90%	2.30%	-2.59	1.01

Table 7.11: The size of the influence, the formation of WADA in 2000 had on all field events where an effect could be seen

Gender	Event	Intervention size (PII %)	+/-	Intervention size (m)	+/-
Women	Long jump	-0.82%	1.42%	-0.05	0.08
	High jump	-0.58%	0.67%	-0.01	0.01
	Discus	-1.53%	1.68%	-0.65	0.71

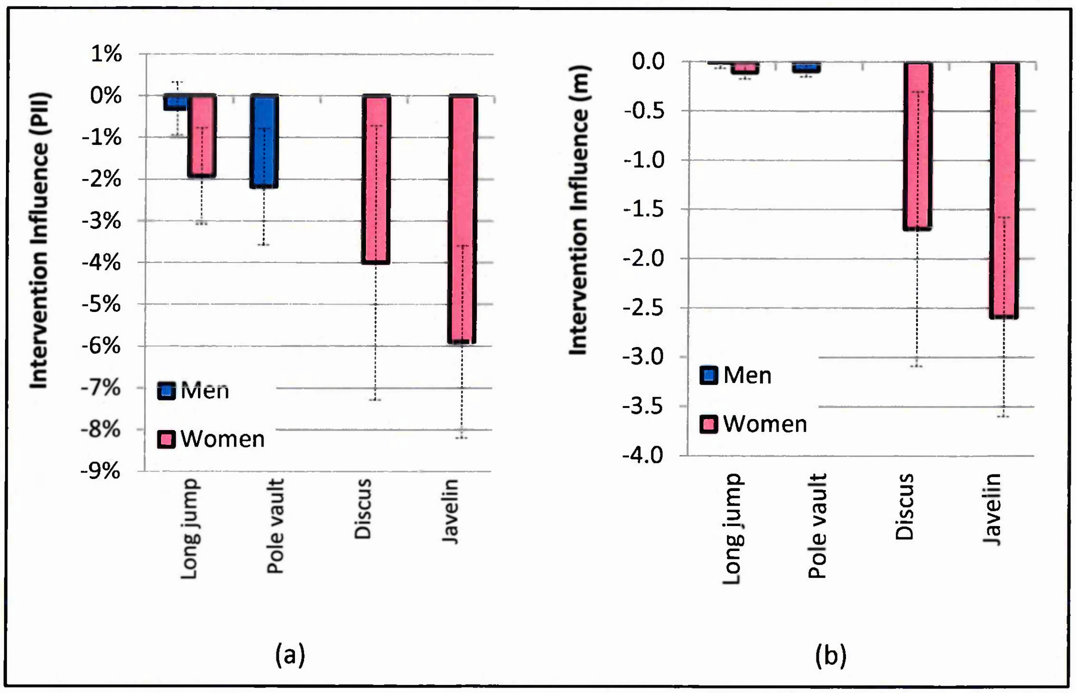


Figure 7.35: The size of the influence, the introduction of random out of competition drug testing in 1989 for all field events where an effect could be seen shown in units of (a) PII and (b) raw distance lost in metres

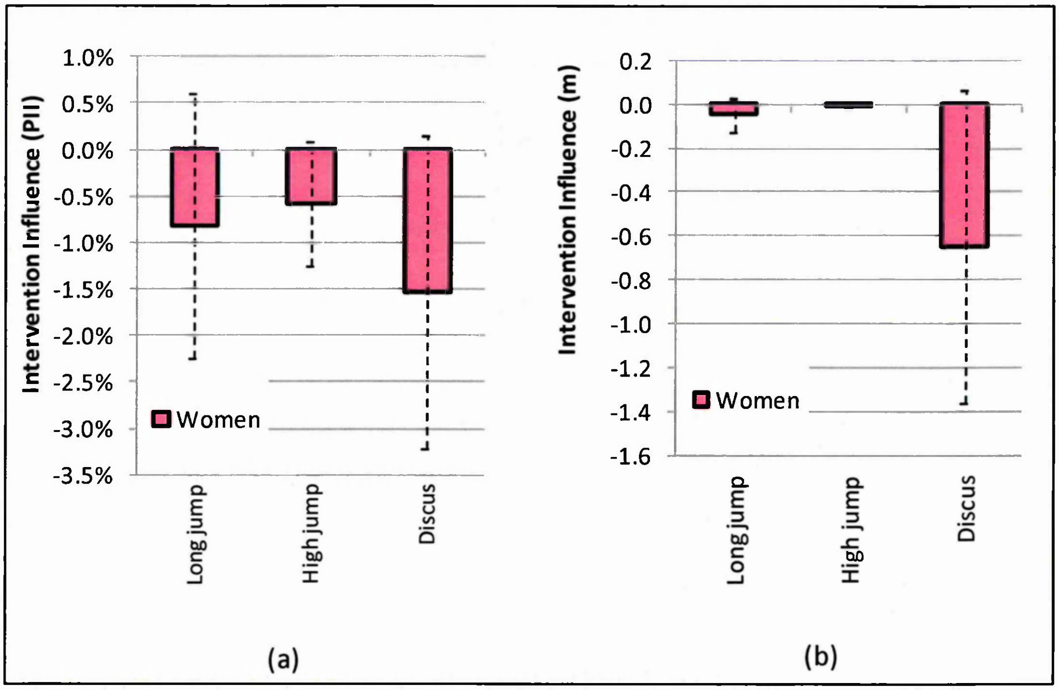


Figure 7.36: The size of the influence, the formation of WADA in 2000 had on all field events where an effect could be seen shown in units of (a) PII and (b) raw distance lost in metres

7.12.b.(ii) Discussion – drug testing technology

It is apparent that not all field events show a step change in performance due to drug testing interventions in either 1989 or 2000. Where drug step changes are not apparent they appear to be part of the linear decline function and cannot be modelled separately. Where a drugs step change intervention is apparent the effects are small, with the greatest influence seen in the women's javelin event, with an influence of 5.90 (+/-2.30) %. Confidence intervals are also high so it is hard to say with confidence whether an effect of drug testing interventions can be seen within the data when modelled with a linear decline function. This indicates that unlike running events, field events saw a less noticeable drug testing step change and the effect of drug testing procedures in field events were much more gradual and followed a linear decline function.

Where step changes were modelled, the effect of each intervention is smaller than the drugs linear uptake peak, indicating the intervention only had a partial effect on drug taking and it took a few years for drugs testing to spread throughout field events. As no men's field events saw a step change in 2000 and confidence intervals for women step change parameters are too high to ascertain the magnitude of the effect it is believe that there is no step change intervention due to the formation of WADA.

As step changes are seen in some events but not others it is believed that a linear decline in field event performance is a mixture of the slow eradication of performance-enhancing drugs from field athlete's bodily systems and also the elimination of performance-enhancing drug use over time with the uptake of better drug testing procedures.

7.12.b.(iii) Conclusion – drug testing technology

It is hard to definitively gauge the influence of drug testing interventions in 1989 and 2000 due to the introduction of better drug testing techniques. Problems have arisen when using the linear decline model in conjunction with a step change in 1989 and 2000. This means, in most cases the step change interventions cannot be meaningfully combined to model step changes as well as the linear decline of performance due to the uptake of better drug testing techniques. It appears that for field events the introduction of better drug testing technologies has a small effect. In contrast, drug testing interventions in running events appear to conform to a step change model and could be down to the shorter period of time athletes stay within the top performance lists, indicated by the number of years runners produce peak performances. This means either side of a drug testing intervention; running athletes may retire or drop out of top performance lists, alleviating any lasting effects of performance-enhancing drugs in running performances.

7.12.(c) High jump – Fosbury Flop

7.12.c.(i) Results high jump – Fosbury Flop

Shown in Table 7.12 are the modelled levels of influence the Fosbury flop technique had in the women's high jump event from 1968 to 1976. Figure 7.37 represents the influence of the Fosbury flop technique in a graphical form. The linear uptake used to model the Fosbury flop did not improve the goodness of fit in the men's event indicating that there was no significance change in performance levels due to the introduction of this technique.

Table 7.12: The size of the influence, the introduction of the Fosbury flop had in the men's and women's high jump events

Gender	Linear peak (PII %)	+/-	Linear peak (m)	+/-
Women	3.69%	1.16%	0.06	0.02
Men	n/a	n/a	n/a	na/

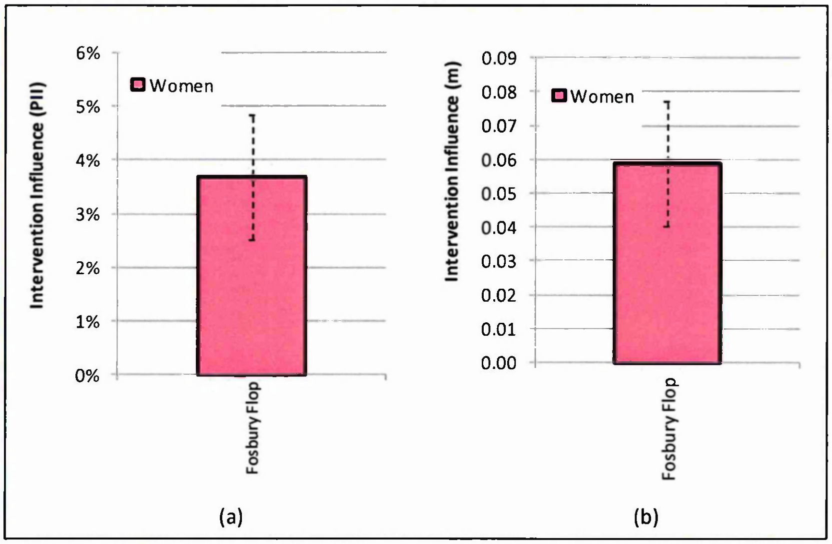


Figure 7.37: The size of the influence, the introduction of the Fosbury flop had in the men's and women's high jump events shown in units of (a) PII and (b) raw height gained in metres

7.12.c.(ii) Discussion high jump – Fosbury Flop

From the results gained in this study it appears that the introduction of the Fosbury flop technique within the high jump event modelled from 1968 up until 1976 had a significant influence on performance in the women's event, but no noticeable effect could be modelled in the men's event. An improvement of 4.58 (+/-1.06) % or 0.07 (+/-0.02) metres was found in the women's event.

The effect of the Fosbury flop could be seen in women's event but could not in the men's event, one reason for this could be that the women's high jump in 1968 was a lot less competitive in comparison to the men's event. The introduction of a new technique such as the Fosbury flop in less developed event may act like a catalyst for improvements in performance by increasing competiveness in that particular event. Competiveness levels in the women's high jump event may have increased to comparable men's levels with the introduction of the Fosbury flop. However, the competitive levels in any events are difficult to quantify or even measure. Due to the nature of the high jump, and the way competitions are decided, the competitiveness levels of this sport directly drives performance levels.

Another reason that the Fosbury flop influenced women's high jump performance to a greater extent could be because the Fosbury flop technique could be better suited to women athletes. The women's high jump event could be more technique orientated than the men's event, with performance improvement in the men's event coming more from increases in power and strength. An improvement in the high jump technique will therefore be more noticeable in the women's event than the men's event. Whatever the real reason it is clear that the Fosbury flop had a greater impact in the women's high jump event in comparison to men's event.

Looking at the evidence gather in this study it appears that the Fosbury flop did little to change the evolution of performances from 1968 to 1976, with small peak values of the linear peak modelling function. The Fosbury flop could be seen as just part of the natural development of the sport and part of the global improvement trend. As mentioned earlier this is in contradiction to existing literature (Balmer et al 2012) who found that there was an increase in performance in the high jump events at the Olympic Games. It is believed that as this current study used a greater resolution of data, the top 25 performance each year in contrast to top 8 Olympic performances, this meant that yearly trends in performance improvement are more apparent.

Another reason for this study contradicting existing literature could be that the nature of the high jump event may be concealing the true impact of the Fosbury flop. Going back to the rules of the high jump, a high jump athlete wins if he or she jumps higher than a competitor, implying the margin of victory only has to be 1 cm or 0.01 metres. If an athlete using an inferior technique can only achieve a certain height, an athlete with the Fosbury flop another possible superior high jump technique only has to better that height to win. This means that the full potential of the Fosbury flop will not be instantaneously seen or noticed within yearly performance figures, but be me apparent in competitions such as the Olympic Games where competitors push each other to greater performances. The full potential of the Fosbury flop may have taken many more years than first envisaged as all athletes need to be using the technique to drive up performance levels through greater competition levels. The optimisation of the Fosbury flop may also take more time and follow a linear uptake function. Therefore it seems that it is very hard to gauge the true impact of the Fosbury flop technique.

7.12.c.(iii) Conclusion high jump – Fosbury Flop

The impact of the Fosbury flop examined through a linear uptake function has been found to be very small in the women's high jump event, but could not be found in the men's event. It is believed the Fosbury flop is part of the natural evolution of high jump performance and is very difficult to isolate using the methods developed for this particular study. The Fosbury flop may have had a more significant impact on the high jump event than that modelled here, and this could be due to the nature of how a competition is decided. It is therefore hard to see the true effect of the Fosbury flop using the current linear uptake functions and performance data sets within this study, but an effect appears to be present in the women's event.

7.12.(d) Pole Vault – composite pole technology

7.12.d.(i) Results pole vault – composite pole technology

The magnitude of the effect of the introduction of composite poles from 1956 to 1972 in the men's pole vault jumping event is shown in Table 7.13 and represented graphically in Figure 7.38.

Table 7.13: The size of the influence, the introduction of composite poles in the men's pole vaulting event

Event	Linear peak (PII %)	+/-	Linear peak (m)	+/-
Men's pole vault	11.07%	3.21%	0.47	0.14

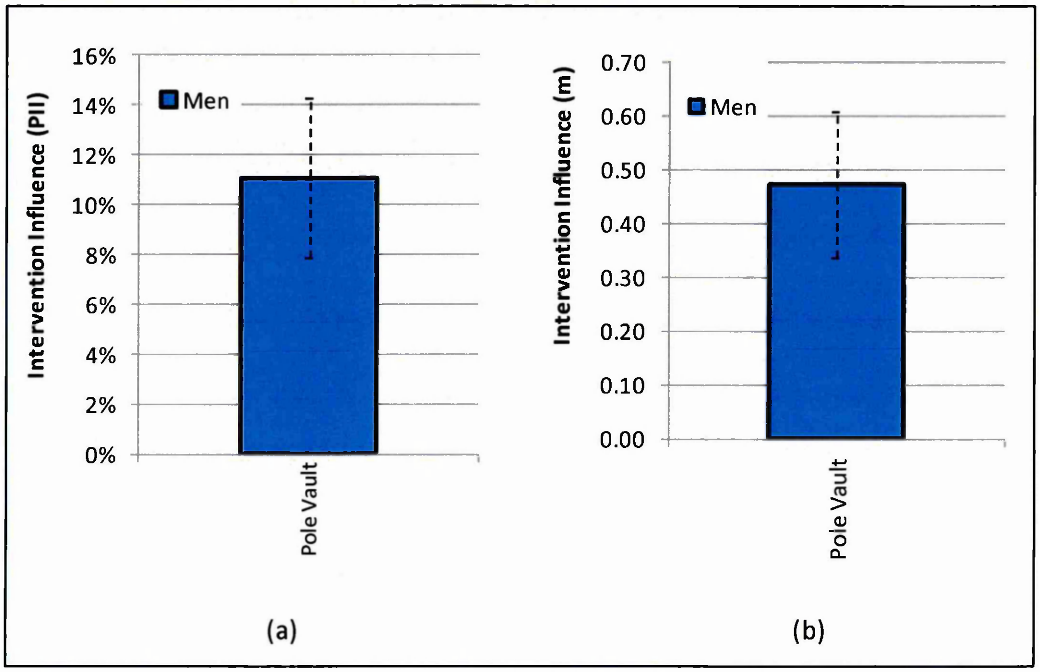


Figure 7.38: The size of the influence, the introduction of the Fosbury flop had in the men's high jump event shown in units of (a) PII and (b) raw height gained in metres

7.12.d.(ii) Discussion pole vault – composite pole technology

The application of the linear uptake improvement function to the men's pole vault event from 1956 up until 1972 to account for the uptake of composite pole technologies shows that there appears to be a significant improvement of 11.07 (+/-3.21) % in the performance improvement index equating to 0.47 (+/-0.14) metres. Women did not compete globally in the pole vault event prior to 1991, and so a comparison between the sexes concerning the influence of the composite poles on performance in not possible.

The pole vault event is similar to the high jump event, in that an athlete wins by out jumping another competitor. The full extent of the effect of the technology introduction like the Fosbury flop of composite poles may have been initially masked due to the nature of competition. The Fosbury flop technique was not responsible for setting a world record in the high jump until 1973, when Dwight Stone jumped a height of 2.30. This is similar to the pole vault, where the first use of a composite pole was in 1956, but it was not until 1961 where the first world record was set using a composite pole (IAAF). During the 1960s there was a large increase in the rate of change of the improvement function and a lot of world records were set during this period. This is in contrast to the high jump event where there is no noticeable increase in the rate of change of the of the improvement function after 1973.

By the end of the technology uptake it appear that all elite athlete were using the new composite pole technology in 1972, where changes to the advances in the design of the poles were halted with new IAAF rulings. However like the high jump the most optimum technique in using composite pole may not have been fully understood in 1972. Another learning or technology uptake of the optimum pole vaulting technique with the new flexible poles may have occurred. So as with the high jump, the full influence of the composite poles in the pole vault event may have had a bigger than measured here using the linear uptake model.

7.12.d.(iii) Conclusion pole vault – composite pole technology

In conclusion there is a significant effect found concerning the introduction of composite poles technologies in the men's pole vault from 1956 up until 1972, this effect is approximately 0.47 m. A large number of world records as well as a visual increase in the rate of change of the global improvement trend is noticed in the pole vault performance figures, but in contrast not noticed in the high jump performance figures. This meant that the composite pole technology has a more tangible and measureable effect than the Fosbury flop technique.

The first world record set using a new composite pole was 5 years after the introduction of the new technology and similar to the high jump. This highlights the possible slow uptake of a new technology in the early stages of the linear uptake function.

Finally as with the high jump, another learning curve prior to the full introduction of the technology of maybe apparent. The optimisation of the pole vault technique using composite poles may have taken the form of an additional linear uptake function, or may be intertwined with the existing linear technology uptake. This means that as with high jump Fosbury flop, composite poles in the high jump may have had a greater influence on performance figures than modelled here.

7.12.(e) Javelin – Rule changes and uptake of hollow javelins

7.12.e.(i) Results – rule changes and uptake of hollow javelins

The effect of the interventions seen in the men's and women's javelin event have been quantified and shown in Table 7.14 and graphically in Figure 7.39. In addition the years at which each intervention occurs in both the men's and women's javelin are shown in the table.

Table 7.14: The size of the influence of the various interventions modelled in the men's and women's javelin events

Gender	Intervention and year(s)	Intervention size change (PII %)	+/-	Intervention size (m)	+/-
Men's	Rule change centre of mass 1986	-12.19%	1.29%	-8.39	0.89
	Tail roughness 1991	0.00%	1.20%	0.00	0.82
	Hollow uptake 1953 - 1956	7.46%	1.49%	5.13	1.03
Women's	Rule change centre of mass 1999	-3.68%	3.16%	-1.62	1.39
	Tail roughness 1991	-0.53%	3.00%	-0.23	1.32
	Hollow uptake 1953 - 1956	6.51%	2.31%	2.86	1.01

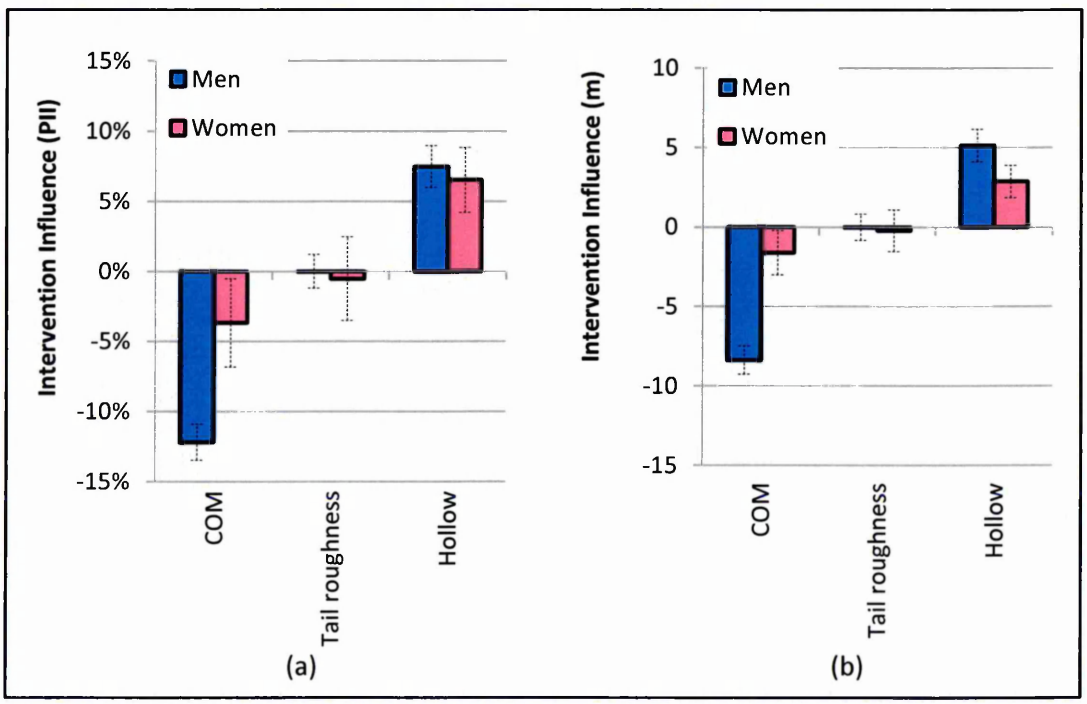


Figure 7.39: The size of the influence of the various interventions modelled in the men's and women's javelin events shown in units of (a) PII and (b) raw distance gained in metres

7.12.e.(ii) Discussion javelin – rule changes and uptake of hollow javelins

Centre of gravity rule change 1986/1999

Overall the intervention with the greatest influence in the men's and women's javelin event is the centre of gravity rule change which took place in 1986 within the men's event. A drop of 12.19 (+/- 1.29) % or a drop of 8.39 (+/-0.89) metres was seen with this rule implementation. The rule change implemented by the IAAF seems to have successfully reduced javelin throws to such an extent that a throw can now be contained within an athletic stadium. The change in the centre of gravity specification in 1999 did not influence the women's javelin event to the same extent as the men's event, only a drop of 3.68 (+/-3.16) % or -1.62 (+/-1.39) metres was apparent. The actual effect of the centre of gravity rule change intervention in the women's event is hard to gauge as confidence intervals are high and the magnitude of the effect small, this means the effect may not be present at all.

The reasons for there being a reduced influence due to the centre of gravity rule change is the women's event could be down to the manner of the rule change as well as the difference in javelin specifications between men's and women's event. The rule change for the men's javelin specified that the centre of gravity has to be moved 40 mm forwards, whereas in the women's javelin the rule dictated that the centre of gravity only has to be moved 30 mm forwards. As the new men's javelin's centre of gravity was more forwards a greater downwards pitching moment is seen during the flight phase, meaning distances thrown will be reduced by a greater extent. This is also compounded by the heavier mass of the men's javelin at 800 g as opposed to the women's javelin at 600 g. This means that the heavier mass of men's javelin will increase the downwards pitching moment further still.

It is apparent that the throwing distance has never been a problem with the women's javelin event, as a typical throw length is approximately 40 m less than men's event. In the women's javelin the centre of gravity rule change was brought in much later in 1999 and was only required to increase the downwards pitching moment of the javelin just enough so that judging landings would be more fair. The aim of the rule change was not to reduce distances and with the evidence gather here, it appears that there is no significant drop in women's javelin performance after 1999.

A diagrammatical representation of forces acting on a javelin during the flight phase is shown in Figure 7.40 and shows the location of the centre of pressure (COP), centre of gravity (COG) and the *d* the distance between the COP and the COG. The downward pitching moment is equal to *mgd* and if *m* or *d* are increased as does the downwards pitching moment and flight time and distance are reduced (Hubbard and Rust 1984).

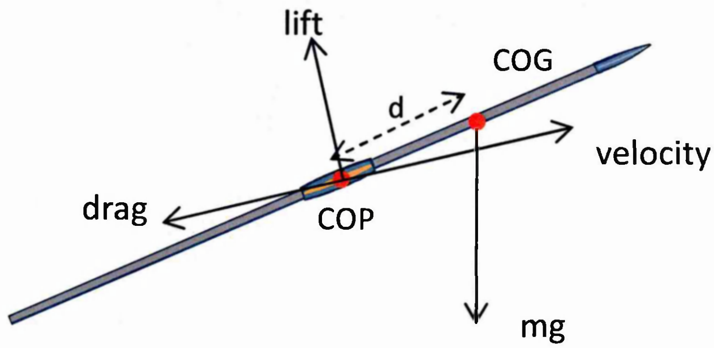


Figure 7.40: Free body diagram of the javelin during the flight phase

Tail roughness rule implementation

Changes to the surface roughness of the tail segment of the javelin in the attempt to reduce pressure drag and increase the performance of the javelin do not seem to have had a measureable effect on performances. The magnitude of step change accounting for the rule intervention outlawing the tail aerodynamic changes is very small, and the parameter error terms is very high. It is believed that there is no significant effect from the aerodynamic changes in either the men's or women's javelin event. Prior to the fitting of improvement functions, further research has revealed that any performances carried out using javelins with tail roughness modifications were disregarded (IAAF). This means that no effect should be apparent when using an improvement function modelling a step change in 1992, and this is what results showed here.

Hollow Javelin uptake

The influential size of the uptake of hollow javelins is again greatest in the men's javelin event at 7.46 (+/-1.49) % or 5.13 (+/-1.03) m compared to an improvement of 6.51 (+/-2.31) % equating to 2.86 (+/- 1.01) m in the women's event. The reduced size of the influence seen in the women's javelin could also be a result of the reduced mass of the women's javelin.

Any increases in surface area due to the hollowing out and widening of the javelin will be smaller with a lower mass of javelin. If the wall thickness, material and mass of the javelin are kept the constant to allow for the same strength, the surface area of the men's heavier javelin will be increased to a greater extent than the lighter javelin. This means more lift will be gained by the greater surface area and hence a superior increase in performance will be seen with the men's specification javelin.

7.12.e.(iii) Conclusion javelin – rule changes and uptake of hollow javelins

The javelin field event sees the biggest change in performance due to an intervention. The specification of the men's javelin was altered specifically to reduce throw distances in the order of safety. From the results gather here it is concluded that this rule change in the men's javelin event in 1986 was successful and did reduce performance by approximately 12.19 % equating to a drop in throw distance of about 8.39 metre. The similar rule change in the women's event had a less significance effect in 1999 and the magnitude of this effect is hard to clearly see and gauge. The aim of the women's specification change to the javelin was to increase the fairness of judging landings and never was intended to reduce distances thrown. From the evidence gathered here the women's rule change also appears to be successful at not decreasing performances significantly.

Changes to tail surface of the javelin to improve performances do not appear to have significantly influenced the performance seen in the javelin events. The rule introduced in at the start of 1992 outlawing the tail surface modifications was modelled with a step change, but no significant step change parameter was found.

Hollow javelins adopted in the early 1950s have appeared to have small influence on performance. This performance improvement seen in the men's event is greater than the women's event and is probably down to the difference in mass of the men's and women's javelin. The men's javelin saw an improvement of 7.46 % and the women's event saw an improvement of 6.51 % in the performance improvement index values.

7.12.(f) Olympic influence

7.12.f.(i) Results – Olympic influence

The size of the Olympic influence in all men's and women's field events is shown in Table 7.15 and resented graphically in Figure 7.41.

Table 7.15: The size of the influence of the Olympics in all the men's and women's field events

	Event	Intervention size (PII)	+/-	Intervention size (m)	+/-	Max effect (PII)	Max effect (m)
Men	Long jump	0.31%	0.18%	0.02	0.01	0.98%	0.07
	High jump	0.17%	0.14%	0.00	0.00	0.60%	0.01
	Pole vault	0.34%	0.36%	0.01	0.02	1.40%	0.06
	Shot put	0.45%	0.54%	0.07	0.09	1.98%	0.32
	Discus	0.48%	0.47%	0.24	0.24	1.90%	0.96
	Javelin	0.20%	0.31%	0.14	0.21	1.02%	0.70
Women	Long jump	0.38%	0.29%	0.02	0.02	1.33%	0.08
	High jump	0.37%	0.21%	0.01	0.00	1.16%	0.02
	Shot put	0.86%	1.00%	0.11	0.13	3.71%	0.49
	Discus	0.97%	0.60%	0.41	0.25	3.13%	1.33
	Javelin	0.52%	0.54%	0.23	0.24	2.13%	0.94

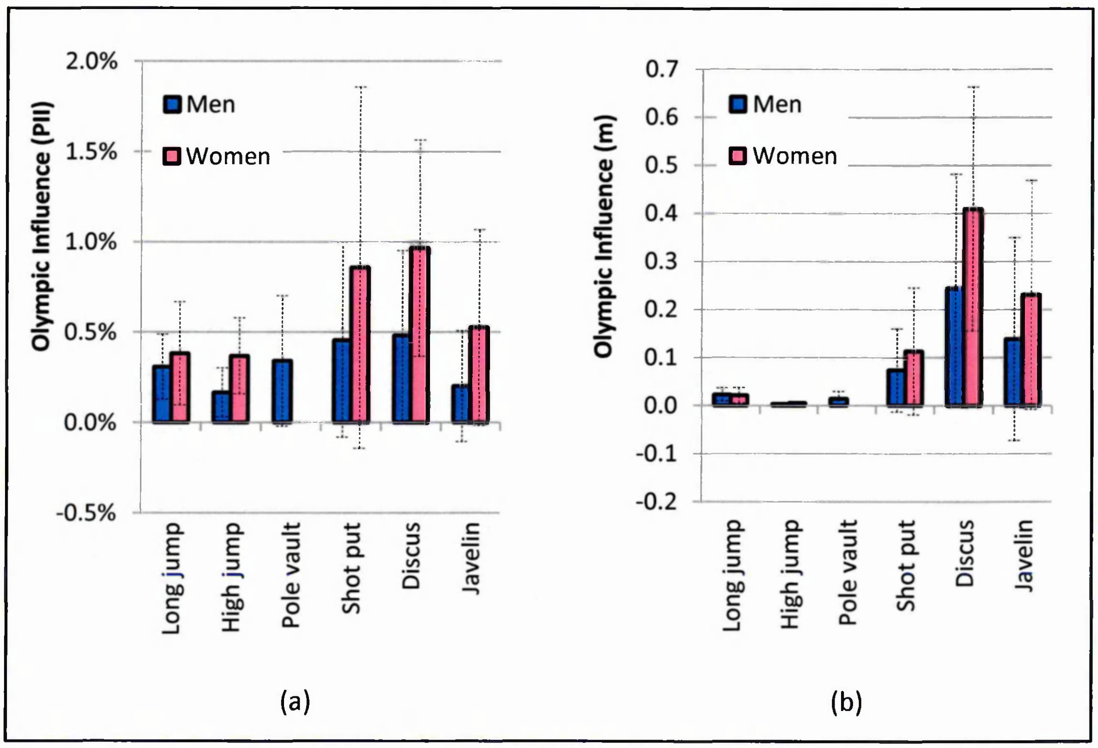


Figure 7.41: The size of the influence of the Olympics in all the men's and women's field events shown in units of (a) PII and (b) raw distance gained in metres

7.12.f.(ii) Discussion – Olympic influence

The size of the Olympic effect in all field events is very small ranging from 0.17% to 0.97% and equating to a peak to trough of about 0.34 % to 1.94% increase in the performance index. The magnitude of the Olympic effect in field events is similar to the effect seen in running events which was gauged at 0.07 % to 0.97 %. Unlike the running events a believed Olympic influence was modelled in all field events. However like some of the running events confident intervals for the Olympic influence parameter in most field events are high in relation to the size of the influence, making it hard to say whether there is an Olympic there at all.

As found with running events, the size of the influence of the Olympic Games years is greater in the majority of women's events when compared to men's event. The reasons for this will be the same as in the running events and has been discussed previous in chapter 6.

The Olympic effect modelled for field events within this study is very small and could possibly be just measuring noise within the performance data set. As the influence of the Olympic Games is very small in both the field events and running events, there is little effect on the size measured interventions.

7.12.f.(iii) Conclusion – Olympic influence

In conclusion, an Olympic sine function has improved the fit of the final improvement function for all field events. However many of the Olympic amplitude terms have high confidence intervals making it hard to accurately gauge this effect, and whether an effect actually exists at all. Men's field events appear to experience a lower Olympic effect when compared to women's events and this is also seen in the running events. The Olympic function could possibly be just measuring noise, but as the Olympic amplitudes are so small they hardly impact on the size of the other measured interventions, but increase the goodness of fit of the final improvement function.

7.12.(g) Limits to athletic performance

7.12.g.(i) Results – Limits to athletic performance without interventions

The predicted limits to the improvement for field events gauged through the global function *L* parameter and without the addition of external interventions are shown below in Table 7.16. Included in this table are also the years at which the improvement function will reach a within 0.1 % PII of that limit. At 0.1% PII within the limit, it is assumed that the improvement function has essentially reached the predicted limit.

Table 7.16: The predicted natural performance limits for all field events examined shown with year at which the improvement functions are within 0.1% of this limit and shown with 95 % confidence bounds

	Event	L parameter (PII %)	+/-	L parameter (m)	+/-	Year when within 0.1 % of limit
Men	Long jump	110.69%	0.97%	8.32	0.07	2016
	High jump	116.24%	0.34%	2.33	0.01	2023
	Pole vault	129.06%	3.64%	5.50	0.16	2039
	Shot put	135.22%	2.97%	21.85	0.48	2004
	Discus	130.95%	0.61%	66.28	0.31	2002
	Javelin	130.84%	4.02%	90.03	2.77	2041
Women	Long jump	124.65%	3.22%	7.06	0.18	2027
	High jump	121.33%	1.74%	1.93	0.03	2019
	Shot put	143.80%	1.63%	18.96	0.22	2000
	Discus	157.17%	3.97%	66.65	1.69	1999
	Javelin	150.33%	7.75%	66.04	3.40	2024

The adjusted limits to performance, taking in to account all the interventions found in each field event has been shown below in Table 7.17.

Table 7.17: New predicted field event performance limits taking in to account interventions since 1948

		L parameter		Technology influnece (Fosbury flop/composite poles/hollow javelins)		Javelin Tail roughness		Javelin COM spec change		Olympic		New limit with interventions	
Gender	Event	(PII %)	(m)	(PII %)	(m)	(PII %)	(m)	(PII %)	(m)	(PII %)	(m)	PII (%)	(m)
Men	Long jump	110.69%	8.32							0.31%	0.02	111.03%	8.34
	High jump	116.24%	2.33							0.17%	0.00	116.43%	2.33
	Pole vault	129.06%	5.50	11.07%	0.47					0.34%	0.01	143.79%	5.99
	Shot put	135.22%	21.85							0.45%	0.07	135.84%	21.92
	Discus	130.95%	66.28							0.48%	0.24	131.58%	66.52
	Javelin	130.84%	90.03	7.46%	5.13	0.00%	0.00	-12.19%	-8.39	0.20%	0.14	124.91%	86.91
Women	Long jump	124.65%	7.06							0.38%	0.02	125.12%	7.08
	High jump	121.33%	1.93	3.69%	0.06					0.37%	0.01	126.25%	2.00
	Shot put	143.80%	18.96							0.86%	0.11	145.04%	19.08
	Discus	157.17%	66.65							0.97%	0.41	158.69%	67.06
	Javelin	150.33%	66.04	6.51%	2.86	-0.53%	-0.23	-3.68%	-1.62	0.52%	0.23	155.36%	67.51

7.12.g.(ii) Discussion – Limits to athletic performance

It appears that a few events have already reached the predicted limit of performance these events are the men's and women's shot put and discus as well as the women's javelin. Other events appear to be close to reaching a limit, these events are the men's long jump, high jump Pole vault and the women's long jump, high jump. Finally there is one event that is predicted to reach a limit in about 30 years; this is the men's javelin.

With these predicted limits it seems that the women's events will improved the most since 1948, with the greatest improvement expected in the women's discus event at a positive 57.17 (+/-3.97) % increase in the performance improvement index. All predicted limits vary from 9.32 % to 35.22 % in the men's field events and from 20.06% to 57.17% in the women's events where it appears there is a great scatter in the limit of performance improvement from 1948. As discussed earlier, much of the discrepancies with the differences in performance improvement limits can be explained by the different levels of competitiveness and development within each sport back at the initial starting point of 1948.

The performance limits in field events may all be reached by 2041, and this is similar to the running events. This means from the middle of the 21st century it is likely that there will be no natural improvement in sporting performance and all events will stagnate. However with the introduction of new innovations and intervention this may not occur.

It appears that the interventions within athletic field events have had a significant influence on current performance levels, and that predicted performance limits have altered accordingly. The intervention that has increased athletic performance levels the greatest is the introduction of composite poles in the men's pole vault event from 1956 onwards. An improvement of 12.36 % to performance levels has been predicted to be caused by the introduction of composite poles and makes up approximately 30 % of the overall improvement in the men's pole vault event from 1948. In other words the composite pole accounts for 0.53 metres of predicted limit of 6.03 metres in the men's pole vault event. The rest of the improvement seen in the men's pole vault event comes from the natural evolution of the sport as well as a possible uptake in learning to use the new poles to their maximum potential.

The largest negative effect was seen in the men's javelin event with the rule concerning the increase in the centre of gravity 40 mm forwards. This intervention had a negative 12.19 % or took 8.39 metres off the total improvement. This large negative influence in performance was offset somewhat earlier by the uptake and use of hollow javelins in the early 1950s. An increase in performance of 5.13 metres or 7.46 % meant that the overall effect from all the intervention in the men's javelin event was only negative 3.26 metres.

The smallest influence measured other than the Olympic effect is the Fosbury flop in the men's event. This saw a slight increase in performance of possibly 2 cm or 0.95 % improvement. This made up about 5.57 % of the overall improvement in the men's high jump from 1948. This is small performance improvement in terms technology uptake, but this possible small margin of improvement is all that is needed to win a high jump event and could be the reason why the Fosbury flop is universally used in the all high jump events today.

As explained in the previous section it hard to predict the absolute limit of performance. Within this section the magnitude of interventions can influence performance a great deal, increasing or decreasing the ultimate performance limit. In the future nobody can predict what interventions will occur, but it is more than likely the predicted limits of performance will be reached soon without any more external interventions.

7.12.g.(iii) Conclusion – Limits to athletic performance with interventions

The predicted limits of field event performance have already been reached in some events and in others it is likely that a performance limit will be reached very soon. This implies that without any external interventions athletic field event performance will stagnate and only small variations due to an Olympic competition effect will be seen in performance trends. Overall women's events are predicted to improve to a greater extent than the men's events form 1948. This can be explained by the levels of competitiveness and development of the different events back in 1948, and that woman's events were at a less advanced stage of development.

In conclusion some limits to performance in field events have been greatly influence by various interventions since 1948, the predicted limits have had to be adjusted accordingly to the levels and effect of these interventions within each field event. Nobody knows what intervention will occur in the future so it is hard to predict what the ultimate levels of human performance will be, but the natural evolution of human performance seems to have already reached a limit in some events and other events this limit will be reached within the next 30 years.

7.13 Chapter summary

Field events can be broken down in to two categories: jumping field events and throwing field events. Depending on the field event performance levels in each event were initially believed to be influenced by technological interventions to varying degrees. Exploring the history, rules and interventions for each field event has shown that there are many interventions which have possibly influenced performance levels. Examining the raw performance data and converting this data in to performance index values from 1948 has illustrated which of the historic intervention are measureable within the field events performance data sets.

A list of interventions and modelling functions required to gauge these interventions was created for each individual field event. Using the goodness of fit value the plausibility of modelling and gauging each individual intervention was assess and where interventions could not be modelled they were left out of the final improvement function model.

All interventions that were found in each field event were gauged and the maximum positive effect from a technology intervention was seen in the men's pole vault event. A summary of all the technology interventions, the global effect of Olympic Games and the final improvement limit values have been summarised in Table 7.18. Performance-enhancing drugs also influenced sporting performance in field events and modelled best with a linear uptake and decline function. Influence from drugs varied from 1.44 % right up to 12.13 %, but it is believed that now performance-enhancing drugs are not significantly influencing levels of athletic performance in field events.

Table 7.18: A summary of the intervention seen in field events

Event	Intervention gauged	Effect size (PII) %
Javelin	Javelin COG rule change	-3.70% – -12.19%
Javelin	Hollow javelins	6.51% – 7.46%
Pole Vault	Composite poles	11.07 %
High jump	Fosbury Flop technique	3.69%
All	Olympics	0.17% – 0.97%
All	Drugs peak	1.44% – 12.13%
All	Original performance limit	10.69 % – 57.17%
All	New performance improvement limit	11.03% – 58.69%

Chapter 8: Freestyle Swimming: Long course

8.1 Introduction

Swimming is another athletic discipline that has developed over the centuries, to one that now comprises of many techniques, distances and events. Swimming events have been part of the modern Olympic Games since their inception in 1896 and now follow a standardised Olympic program, with all races taking place in a 50 metre pool.

Swimming to humans is believed to be less natural than the other athletic disciplines, as not every human possesses the ability to swim and an aquatic environment is not a normal habitat for humans. As swimming is not an innate human ability the development of faster swimming techniques is believed to be an on-going process as the optimum technique may have yet to be achieved. This is unlike running, where humans can instinctively achieve an optimum running style for their physiology. In addition to this it is believed that swimming is an athletic sport heavily influenced by technological changes, as these technologies can easily alter the athletic task of swimming competitions, and thus dramatically change measured swimming performance. Some of the technologies believed to influence swimming performance are the introduction of full body swimming suits, the use of goggles, and also the adoption of damping lane ropes which reduces drag inducing turbulence. The aim of this chapter is therefore to identify and quantify the interventions and technologies that have significantly influenced swimming performance from the baseline year of 1948. The aim of this chapter can be broken down in to the following objectives:

1. Explore the nature and intervention history in the athletic sport of swimming
2. Gauge the performance improvements in the sport of swimming
3. Identify the interventions that are believed to be present
4. Apply intervention modelling techniques to swimming performance data
5. Explore the magnitudes and types of interventions seen in freestyle swimming and make comparisons to the other athletic events examined so far.

8.2 Swimming

There is evidence that human swimming techniques have existed for thousands of years. Cave paintings and drawings from Babylonians and Assyrians depict human swimmers using a breaststroke technique and are dated at around 4000 B.C. As the earth is covered by approximately 70% water, for survival humans were inevitably going to gain the knowledge of how traverse areas of water by swimming. Even though humans are widely accepted to have first evolved to be land mammals, the controversial "Aquatic ape hypothesis” suggests that the common ancestors of modern humans spent a period of time adapting to life in an aquatic environment (Moore 2011). This theory is brought about by the undisputed notion, that early Homo sapiens were better suited to aquatic environments than other great apes.

8.2.(a) History of competitive Swimming

There is no historical evidence showing that swimming events made up part of the Ancient Olympic Games, despite there being evidence that swimming competitions were already being held in other areas of Greece. Greek historian Pausanias comments on early swimming competitions held by Greeks in his descriptions of Greece (Oppenheim 1970). After the Greeks, the Romans were thought to be the first to create man made swimming pools, and held swimming competitions accordingly. There are also records of swimming races held around 36 B.C. in Japan for Samurais. Japan is also thought to be the first country to introduce a national sports organisation for swimming in 1603. The Japanese swimming organisation managed a swimming school curriculum and held inter-school competitions which are still on-going in Japan today. Competitive swimming in Japan historically remained closed to the outside world, and it was not until the 19th century where globalisation allowed truly international swimming competitions.

Modern swimming competitions can be said to have started in London in 1837 with the first competitive races organised by a sports society, called the National Swimming Association. The first international competitions were thought to be held in Australia in a so called 100 yard "World Championships" on the 9th of February 1858 (Oppenheim 1970).

Later in 1869 in London the M.S.C.A. the Metropolitan Swimming Club Association was formed and was the first federation of clubs. The federation was formed to standardise rules for swimming competitions. Five years later in the 1874 the London Federation became a national federation known as the Swimming Association of Great Britain. Swimming federations had also been formed in other countries around this time; an example being the Erste Wiener Amateur Swim Club of Vienna, Austria.

Swimming events were held at the first modern Olympic Games in Athens 1896, however there were only three events and were not as high profile as the track and field events. Swimming events at the next few Olympic Games gained status and popularity and in 1904, St. Louis, USA the 50 yard freestyle, 100 yard backstroke and

440 yard breaststroke were added to the programme. The 1904 Olympics was also the first to hold swimming events in a purpose built still water artificial lake.

Before the 1908 Olympic Games it was realised that swimming needed to be unified to allow for fair and standardised events to be held a succeeding Olympics. This then lead to the formation of FINA, Federation Internationale de Natation Amateur in London, July 1908. The original threes aims of FINA were as follows: (1) To establish rules for swimming events, rules applicable for all international competitions, (2) keep a list of world records and to verify whether performances put forward as records were established in complying with the ruling, (3) To organise the swimming competitions of the Olympic Games. The code of the English Swimming federation was the basis of the formation of FINA. Since 1908 FINA has been the international governing body for Swimming, which has governed the rules for Swimming for over 100 years.

8.2.(b) Swimming strokes

The evolution of competitive swimming strokes came from the constant need for improvements in swimming speed. The modern evolution of different strokes started at the beginning of swimming races in England around the year 1830. During these early English competitions only the breast stroke existed. As more international competitions began, the introduction of different strokes was seen. Some of these strokes had been developing for maybe thousands of years in different areas on the planet. In particular Native Americans used a stroke which was much faster than the English breast stroke, and this stroke later developed in to the modern day front crawl. In the early days of swimming competitions there was no definition or rules which governed which swimming stroke could be used. These were essentially "Freestyle" competition where just about anything was accepted. As the front crawl (otherwise known as the Trudgen, named after the man who introduced it to England) was emerging as the fastest stroke this became the dominant stroke used in swimming races. Breast stroke was still used to compete with but in specific races. There were a few variations of the front crawl, the most noticeable was the English side stroke which evolved from an Aborigine swimming technique. Definition of specific strokes followed with the unification of rules and the creation of FINA in 1908. Now today there are four specific strokes. These are the front crawl or freestyle, the breaststroke, the backstroke and the butterfly. The butterfly stroke evolved later, from the original breaststroke technique.

The distance over which these strokes were competed has also changed since the start of competitions. The format of the early Olympic swimming races were set by the event organises prior to the formation of FINA in 1908. With the evolution of swimming strokes like the butterfly and the standardisation of pool sizes over the 20th century, it has only really been within the last 40 years where a standard set format of race distances for different strokes has been formed. However events like the 100 and 200 metre free style and breaststroke events have a long history and records go back to the start of international competition. According to FINA there are currently two lengths of pool which official competitions are held. These are the 25 metre pool, or short course and the 50 metre pool, or long course. All Olympic swimming events are now held in long course pools.

8.2.b.(i) The freestyle

The front crawl is the fastest swimming stroke and therefore always used in the freestyle swimming event. Unlike the other swimming strokes there are no rules which specify the technique in the freestyle event. The front crawl stroke is performed on the swimmer's front, close to the water's surface and with the body in as horizontal position as possible. The frontal area of the swimmer is kept to a minimum as the stroke is performed in the longitudinal axis, meaning the arms and the legs do no move far from the centre line of the body. The legs perform a "flutter" kick behind the swimmers body and the arms perform a forward crawling motion in front of the swimmer (Counsilman 1968). The crawling motion of the arms is where the stroke gets its name from. The five stages of the front crawl are depicted in Figure 8.1.

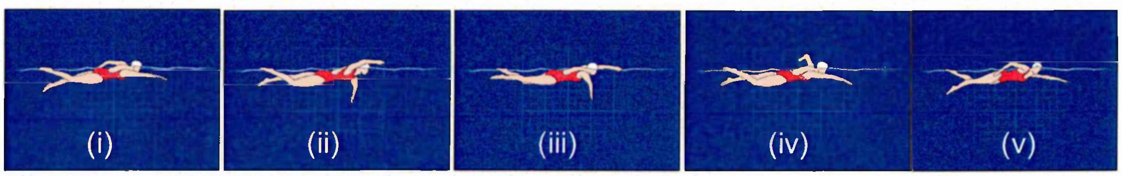


Figure 8.1: The five stages of the front crawl (freestyle) stroke (BBC Sport 2005)

8.2.b.(ii) Starting, turning and finishing a swimming race

The start of a swimming race is similar to a running race. Swimmers line up on the edge of a pool on starting blocks and start on the orders of starting official. Originally there was a starting gun and no starting blocks, but as technology developed electronic starting and finishing systems were employed much like running events. Upon starting a race the swimmers dive in to the pool and perform a specific technique under the water to take them in to the swimming stroke. The only event that does not start on the side of the pool is the backstroke. When reaching the end of a pool a swimmer performs a turn with a technique that is stroke dependent, this is usually a form of tumble turn where the swimmer rolls and pushes off the wall and in so changes direction. To finish a race a swimmer must touch the end wall with either both hands in case of the breast stroke or the butterfly or a single hand in the case of the front crawl or the back stroke. Originally a timekeeper would judge the finish and time the race using a stop watch but this later made way to electronic timing systems. Judges are still employed to make sure that the correct starting techniques, swimming strokes and the correct finishing technique is used by all swimmers.

8.2.(c) Modern competitions Olympic Games and World championships:

Over the past century swimming competitions have grown to consist of many events, strokes and disciplines. Swimming events at the Olympic Games have been standardised to consist of the following long course events, held in a 50 metre pool:

- Freestyle (Front crawl): 50 ,100, 200, 400, 800 &1500 metres,
- Backstroke, Breast stroke and Butterfly: 100 & 200 metres,
- Individual medley 4 x 100 metres (Butterfly, Back, breast, & freestyle),
- Relays: 4 x100 metres and 4 x 200 metres Freestyle, 4 x 100 metre Medley (Back, breast, butterfly & freestyle).

The most recently introduced event at the Olympic Games is the open water 10 km marathon event (Freestyle), but this is not governed by FINA. Short course (25 metre pool) competitions are also held but not at the Olympic games. The short course World Championships also includes the 50m back stroke, breast stroke and butterfly events in addition to the existing Olympic distances.

8.2.(d) Result statistics available: freestyle swimming

Upon examining the performance statistics it appears that swimming performance statics and records are not as complete as track and field athletic events. World records date back to the creation of FINA in 1908 and there are some early performance records of swimming from the first Olympics Games in 1896, but these swimming events were held in open water and different conditions. There are detailed yearly top performance lists for each event but these lists are only available from 1990 onwards. The only performance data sets found to go back to 1948 are the yearly top 3 performance lists for some men's and women's freestyle events. These specific freestyle events are the men's 100, 200, 400 and 1500 m and the women's 100 and 200 m. As the only complete swimming performance data sets are for the freestyle swimming event, for the purposes of this study, the influence of historic interventions will be gauged in these specific freestyle swimming events using the methods described in chapters three through to five.

8.3 Interventions in swimming events

There may have been many historic interventions that have influenced swimming performances. Interventions that have possibly influence swimming performances from 1948 have been summarised in the time line show in Figure 8.2.

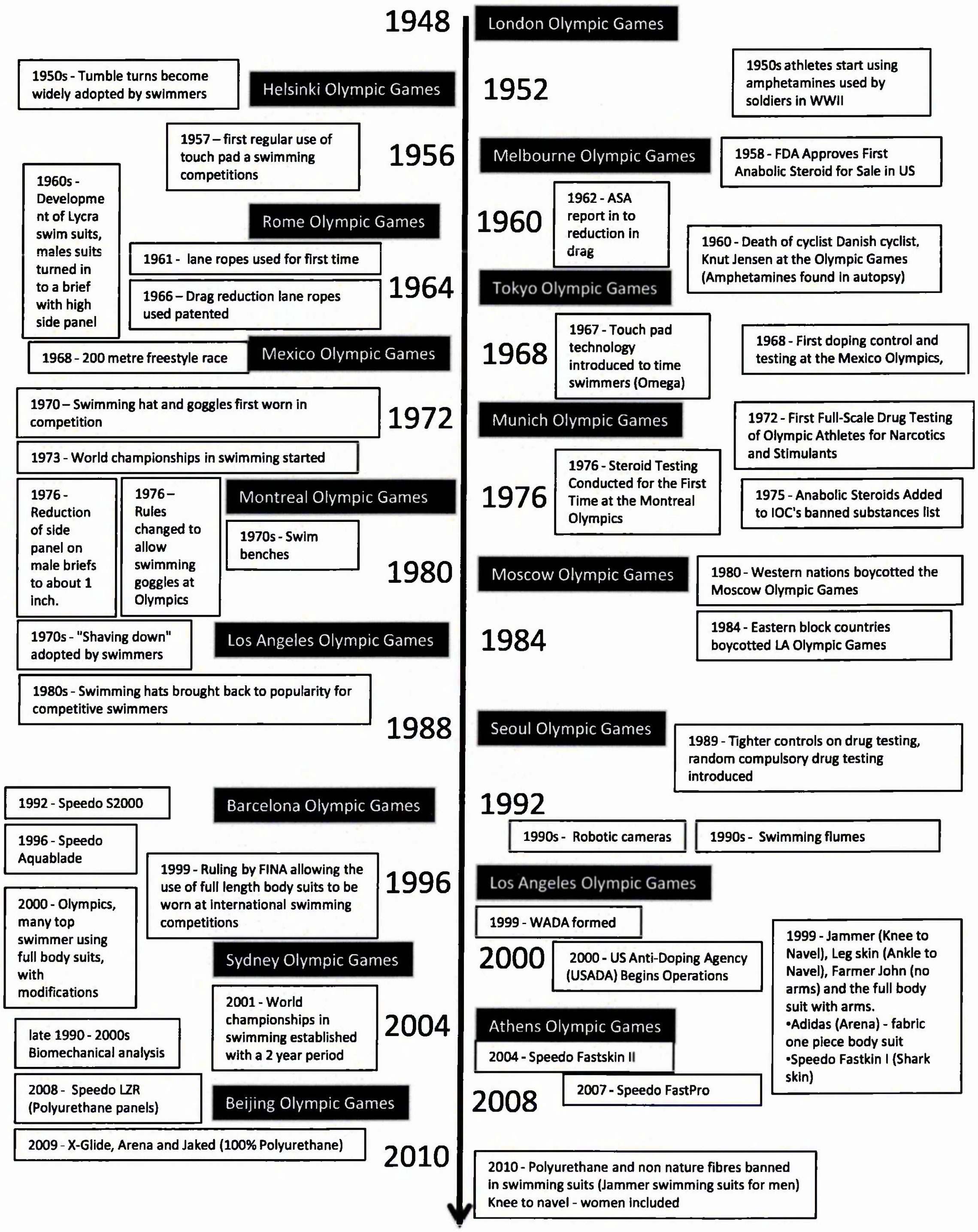


Figure 8.2: Time line of interventions from 1948 for swimming events

8.3.(a) Origins of swimming suits

The interventions arising from changes in swimming suit design are the first to be explored. Most swimming competitions up until the middle of the 19th century were competed in by swimmers that were completely naked, as this was believed to be the best way to optimise swimming performance. With the advent of gentlemanly swimming clubs in Victorian times, swimming suits were invented to cover the human body in accordance to morality of the period. These swimming suits were made of knitted woollen materials and were very heavy when wet. In the mid to late 19th century rules for what swimmers could where when swimming during competitions were set by the by the Amateur Swimming Association (ASA). An example of the swimming attire of the 19th century for men and women is shown in Figure 8.3.

(a) (b)

Figure 8.3: Depiction of the swimming typical swimming attire used in the 19th century (a) men and (b) women

The first change made to the original swimming suit design was in 1924. Swimmers from the British Olympic team wore outfits made of silk, these suits were lighter and more comfortable than the original woollen suits and were considered to be performance-enhancing. The problem with the silk suits was that they were very expensive. The introduction of artificial Rayon fibres in the 1930s reduced the cost of manufacturing similar swimming suits to those made of silk. Also in 1935 topless swimsuits were used by male swimmers in competition for the first time.

Developments in swimming suit technology were halted due to World War II. After the war, the next step in swimming suit design came with the invention of Nylon fibres. Nylon fibres allowed manufactures to create even more comfortable and inexpensive swimming suits. In 1962 the ASA commissioned a report concerning the issue of "drag" in swimming. It was acknowledged that costumes create drag or friction in the water which means swimmers do not swim with 100% efficiency. The report concluded that there were two ways to reduce the drag: (1) Design a better fabric where the drag coefficient gets closer to human skin against water, and (2) reduce the amount of the suit on the body.

Soon after this report, in the mid to late 1960s, a Lycra and nylon fabric blend enabled manufacturers to create stretchy tight fitting costumes to minimise drag further still. The 1960s saw male competitive swimmers using a brief style suit with a high side panel, this later changed in the 1976 Olympics to a hip brief with an inch side panel. This later brief style swimming costume for males is known today as "speedos". Women wore a corset style swimming suit with a flared skirt in the 1960s but the skirt was lost by the 1976 Olympic Games. Today this is what is now seen a standard one piece swimming costume for women. Swimming costumes for both men and women stayed like this for the next 20 or so years, with only minimal changes to shape and cut of these swimming costumes to minimise fabric use and reduce drag.

8.3.(b) Swim suits of the last 20 years

The first swimsuit that claimed to overcome the issue of the drag was the Speedo S2000. This suit was claimed to have a lower drag coefficient than shaved skin and was billed as 15% less drag than conventional swimwear fabric. Following the S2000 was the Speedo Aquabade, which was billed at reducing turbulent drag and have "8 % lower surface resistance than the S2000" (Speedo 2011). Up until the late 1990s the traditional male trunks and female one piece suits were still employed, but as newer materials were used in swim suit manufacture and skin drag of these suits were reduced further still suit manufacturers decided to create swimming suits that cover the majority of the body. In 1999 FINA allowed the use of full length body swimming suits at international competitions, Adidas (Arena) launched a fabric one piece body suit and Speedo launch the Fastskin I. At the 2000 Olympic Games in Sydney Australia many swimmers wore full length body suits. In 2004 Speedo launched another suit, the Fastski II and claimed to reduced drag by 4 % over the FastSkin I. Finally in 2007 Speedo launch the last full body suit made full of a fabric material, the FastPro and this suit claimed to compress the wearer up to 15 % more, was slower to absorb water and provided 5 % less passive drag than the Fastskin II, however this suit never really caught on.

The most notable introduction of a swimming suit was in the 2008 Olympic year. Speedo launched the FastSkin LZR swimming suit which consisted of non-fabric polyurethane panels strategically placed on the suit to reduce drag. There was controversy surrounding the new LZR suits as they appeared to substantially improve swimming performance with many world records being set at the heat stages of the Olympic Games. Another controversial point was that the LZR suits were not available to all athletes. Speedo claimed to that the LZR suit reduce drag by 24% compared to other previous suits and gave 38% less drag than the traditional Lycra suit.

Another leap in swimming suit technology came in 2009 with the introduction of full body suits made completely out of polyurethane. Suits like the X-Glide made by Arena and the Jaked were examples of these new suits. During this season even more world records were set in many swimming events and many of these were at the 2009 swimming world championships in Rome. The full polyurethane suits took drag reduction further, as no part of suit was made from traditional fabrics.

During 2009 FINA decided to enforce a rule stating that the use of non-fabric materials as well as the use of full length body suits would be banned for use from the 1st of January 2010. The new regulations effectively banned all advances in swimming suit technology and now currently the men's swimming suits is a "Jammer style" which allows material from the knee to the waist and the women's suit which allows materials from the knee to the shoulder.

8.3.(c) Shaving down - Reduce skin drag

The term shaving down refers to the action of a swimmer shaving their body hair in order to make the skin surface as smooth as possible before a competitive swimming race. A smooth skin surface is believed to enhance swimming performance by reducing skin friction drag, and lowering the energy cost of swimming (Sharp et Costill 1989). In the process of shaving down, not only the hair is removed, but a thin layer of dead skin is also removed. The removal of the top layer of skin reveals a sensitive layer of new skin cells and in turn a heightened feel for the water, this heighten feel for the water may or may not be a placebo effect and could make the swimmer feel faster. Shaving down in swimming started in earnest around the 1970s and is still practiced today in a variety of different sports. The need to shave down was reduced in swimming with introduction of full body suits at the end of the 21st century, however with recent rule changes to only allow reduced covering swim suits will mean shaving down will be brought back to popularity.

8.3.(d) Swimming hats/hats

Swimming caps were originally created at the start of the 20th century and were for originally used by recreational bathers to protect their hair from the water. The original style was described as an "Aviator style" which had a chip strap. The original swimming caps were made from rubberised fabrics and then later in the 1920s swimming cap material moved on to latex rubber. Swimming hats went out of fashion in the 1960 with bathers as developments of shampoos alleviated the need to protect the hair. A swimming hat and goggles was first worn in elite competition in 1970, by David Andrew Wilkie of Great Britain. After this hats were adopted by all competitive swimmers to reduce drag caused by head hair. Current competitive swimming caps are made from either a Lycra or silicone material blend and are now part of the standard equipment for any competitive swimmer (Swim Cap 2011).

8.3.(e) Timing systems in Swimming

As mentioned previously, the 1968 Mexico Olympic Games saw the first use of electronic recorded race times as official figures in all events. At the 1968 Olympic Games swimming events were now started by an electronic speaker system behind each swimmer. The timing system was then stopped at the end of a swimming race by the swimmer touching a touch pad system. Even though the new electronic timing systems in swimming had an accuracy of 1/1000th of second, world records around this time were still quoted to 1/10th of second (OMEGA 2011). It appears from examining the available result statistics, swimming results started to be officially recorded to 1/100th of a second in 1971. However it is not clear whether the official swimming statistics before this date were gained with manual timing systems or electronic systems rounded to the nearest 10th of a second.

8.3.(f) Swimming pools

The first swimming pools are thought to be first devised by the Romans, but it was not until the middle of the 19th century where indoor swimming pools became popular in modern world, where Victorian England saw the modern development of swimming pools alongside swimming as a sport. Since the mid-19th century, competition swimming pools have developed over time from small modest establishments to massive international sporting venues holding thousands of people. Modern pools incorporate design developments which have perhaps noticeably increased swimming performance. Modern pools are now very deep and are surrounded by large gutters. These design enhancements dampen turbulent waves generated by the wake of a swimmer, which in turn stops the turbulent wake interfering and increasing the drag on a swimmer. Reducing the drag a swimmer experience will in turn increase swimming performance. Another design enhancement to reduce a swimmers trailing wake was from the invention of turbulent reducing lane ropes, which were patented in 1966. These new lane ropes have the same effect as large gutters at the side of the pool in that turbulent waves are damped and do not bounce into the path of another swimmer.

8.3.(g) Swimming goggles

The use of swimming goggles was first allowed at the 1976 Olympic Games. The most obvious use of swimming goggles is to allow for better visibility in the pool which means that a swimmer can see where they are going more clearly which allows for more accurate turns and finishes to be made. The increased visibility that goggles may have a small beneficial influence on performance. However, the most beneficial impact from swimming goggles is believed to be from the increased in water training time that wearing goggles facilitates. Swimming goggles protect a swimmer's eyes from chlorine and irritation from the swimming pool and as such goggles can be classed a training aid.

8.3.(h) Training aids

As well as swimming goggles, there are many more training aids that have possibly influenced swimming performance. Biomechanical analysis started in 1928 where at the University of Iowa coach David Armbruster filmed swimmers underwater with the aim of perfecting the swimming strokes. Around the same time Japanese coaches were using underwater photography to analyses swimming strokes and in the 1932 Olympic Games Japanese Swimmers dominated the medals tables. Later in the mid-1950s a visual pace clock was invented which allowed swimmers to keep pace without the need for coaches to use stop watches. Later in the mid-1990s new training aids were introduced, these included: swimming flumes, swimming benches and underwater robotic cameras. These modern training aids may have also increased swimming performance. The introduction of swimming training aids and their subsequent influence on swimming performance is believed to be small. In addition, the effect of training aid introduction is particularly hard to gauge as the year of their introduction is difficult to specify. As such training aids interventions will be treated as part of the overall global performance improvement trend and accounted for within the exponential function.

8.4 Results – Swimming performance improvement

The evolution of performance in the men's and women's freestyle swimming events has been shown as raw performance time in seconds against historic year in Figure 8.4.

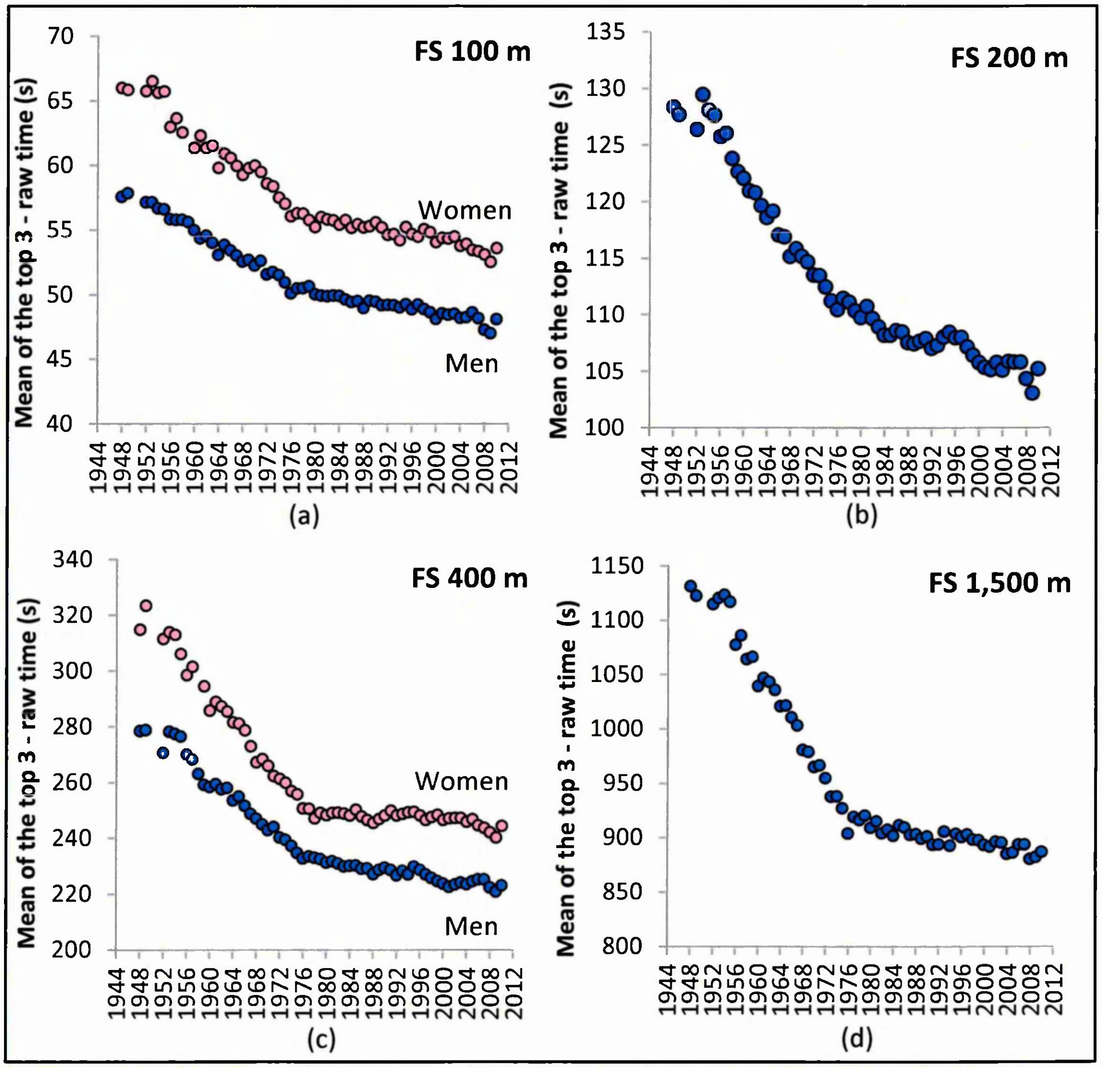


Figure 8.4: Mean of the top 3 raw swimming performance data from 1948 in the men's and women's freestyle event with a distance of (a) 100 m, (b) 200 m, (c) 400 m and (d) 1,500 m.

The raw performance times have been converted into average speed in completing the swimming race and are shown for each year from 1948 in Figure 8.5.

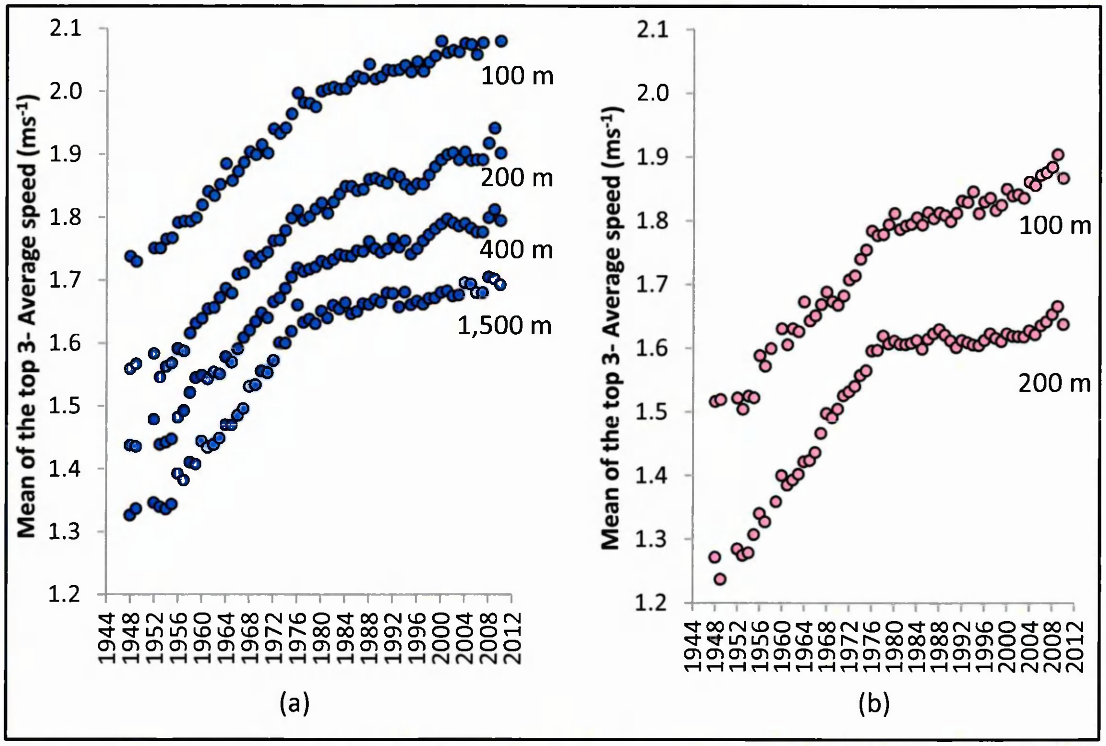


Figure 8.5: Mean of the top 3 swimming performance data converted into the average speed to complete the race for each year from 1948 in the freestyle events for (a) men, and (b) women.

The raw performance figures have now been converted into a performance improvement index values, each year from 1948 and are shown in Figure 8.6.

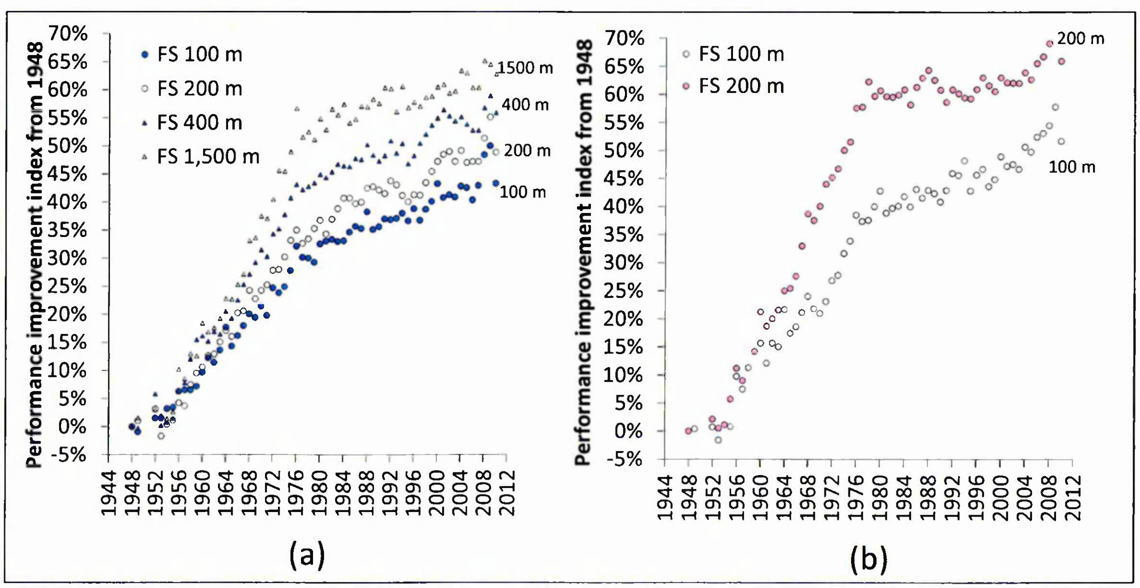


Figure 8.6: Mean of the top 3 swimming performance data converted into a performance improvement index from 1948 in the freestyle events for (a) men, and (b) women.

For each freestyle swimming event the maximum magnitude in terms of percentage increase in the performance improvement index, and the year at which this maximum value was found, has been represented graphically in Figure 6.10.

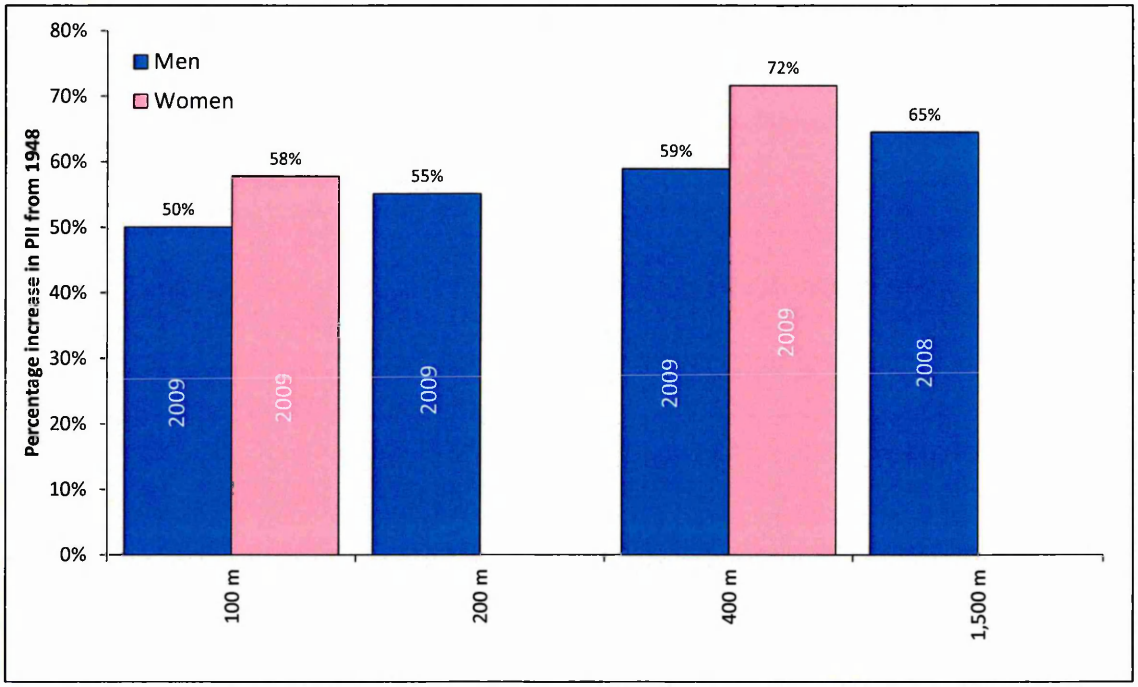


Figure 8.7: Maximum percentage increase in the performance improvement index from 1948 for all freestyle swimming events, shown with year of peak performance.

8.5 Discussion – Swimming performance improvement

8.5.(a) General trend of improvement

It appears that across all event freestyle swimming events an underlying universal improvement trend is apparent. The general improvement trend seen in freestyle swimming events appears to conform to the characteristics of an exponential decay function and similar to the trends observed in all track and field sporting events. The similarity in improvement trends between the different sporting events indicates that performance evolution is driven by similar factors in all events. The primary factor which drives performance improvement in all sporting events has been hypothesised to be the increase in size of competing population. Other factors which are believed to drive the evolution of all sporting performance have been the improvement of training methods and development of nutritional knowledge. One additional driving factor which may have contributed to the evolution of swimming performance has been the continued development of swimming techniques. As swimming is not a natural human movement in comparison to running or throwing it is believed there is more scope to optimise swimming techniques. Throughout history any small changes in the freestyle stroke as well as the introduction of techniques like the tumble turns may lead to significant performance improvements. However it is believed that the optimisation of swimming techniques takes place over a long period and any instantaneous performance improvements cannot be observed. Any improvements in performance due to enhancements in swimming techniques may need to be modelled as part of the global improvement trend.

The maximum increase in performance improvement observed across all freestyle swimming performances is between 50 % and 72 %. This margin of improvement is larger than all running events and the majority of field events. The larger margin of performance improvement observed in freestyle swimming has primarily been attributed to the greater scope for optimisation of techniques within swimming. Additionally, in 1948 the level of competitiveness in swimming is believed to be a lot lower in comparisons to other athletic events at that time. There was most likely a significant lower competition population in swimming events in 1948 compared to other athletic events, meaning the initial observed performance levels in swimming would have been lower. Fewer swimming pools meant lower numbers of athletes could access the pools which in turn meant the percentage of the global population which could swim at all was significantly lower than it is today. This is unlike running events where no particular techniques or special venues are required to participate in running events.

8.5.(b) Men versus women

In comparable freestyle events men are faster than women, and this is attributed to physiological differences between males and females. These physiological differences found in elite male athletes, such as a greater percentage of lean muscle mass and reduced fat stores are the same reasons why men out perform women in other athletic events.

Women appear to have experienced a greater performance improvement in comparable freestyle events, with a 58% increase in performance in the 100 m events compared to an improvement of 50% for men. This finding is also the same as the other athletic events examined so far and is attributed to women's sport being in a less developed state in 1948 when compared to men's sport. However it appears in freestyle swimming events the gap between performance improvements between the genders is smaller and implies that the competitiveness levels between men's and women's swimming events were closer together at the baseline year of 1948.

8.5.(c) The effect of distance on swimming performance

Examining the men's events, it appears that the longer the race distance the greater the maximal performance improvement. There could be many reasons for an increase in performance improvement in the longer distance events. Firstly the developments of the freestyle swimming technique may have evolved so that efficiency saving could be made in the longer distance events, which are not so prominent in the shorter distance events. Secondly training knowledge, which maximises swimming endurance may of have had a greater beneficial influence on longer distance events than the shorter distance events. Finally a reduced size in the competition population in the baseline year of 1948 could be apparent in the longer distance events, meaning baseline performance figures were lower than other events.

The greater the distance of the freestyle event the slower the average swimming speed, this relationship between average completion speed and race distance has been shown for performance figures taken from the year 2010 in Figure 8.8. This graph will be used later on to explain the differences in the believed effect of swimming suit technology.

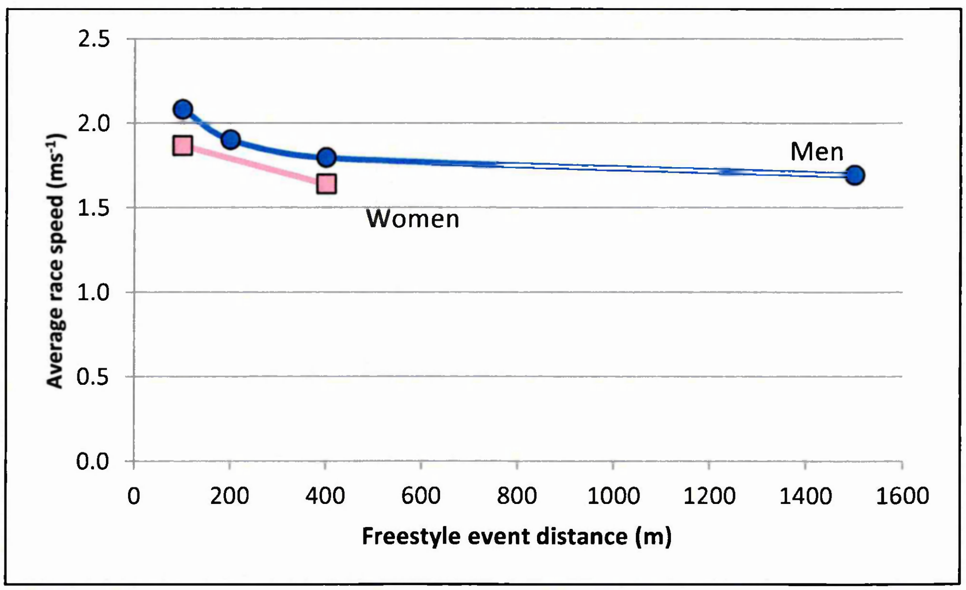


Figure 8.8: The average speed to complete a freestyle event against race distance for the mean of the top 3 performers in 2010

8.5.(d) Intervention – The polyurethane swimming suit

The maximum performance improvements in freestyle swimming events from 1948 appear to be all set in the year 2009, apart from one exception the men's 1500 m, which showed a peak in 2008. These peak years tie in to the introduction of polyurethane panelled suits and full polyurethane suits in 2008 and 2009 respectively.

The rule change in 2010 which banned the use of polyurethane swimming suits in competition resulted in a drop in performance levels. The performance levels in 2010 are believed to have reverted back to the global improvement trend with 2007 being the last year that conformed to this trend.

8.5.(e) Intervention – Technologies taken up in the 1970s

In the 1970s there appears to be an increase in the rate of change of performance improvement before a sudden decrease from the 1980s onwards. Freestyle swimming performances after the 1980s may be approaching a theoretical performance limit, due to the exponential decay nature of the improvement trends this could be why the rate of change witnessed in performance improvements has slowed down. In the 1970s the increase in the rate of change of freestyle swimming performance which does not conform to the exponential trend could be attributed to the uptake of technologies such as swimming hats, shaving down and goggles which have been found to be introduced in this historic period.

8.5.(f) The effect of the change in data set - mean of the top 3

The only historic data available for any swimming event was the yearly top 3 performances in the long course freestyle event. This means that there was a forced reduction in performance data used to carry analysis in this sport. However, it is believed that this will not significantly influence performance index calculations and the calculated size of any interventions. Using performance data from the men's 100 m running event the likely effect of the change in performance data set can be established. Comparing the average differences between the mean of the top 25 to the mean of other top performance lists in the men's 100 m running event a trend is apparent, this trend is shown in Figure 8.9.

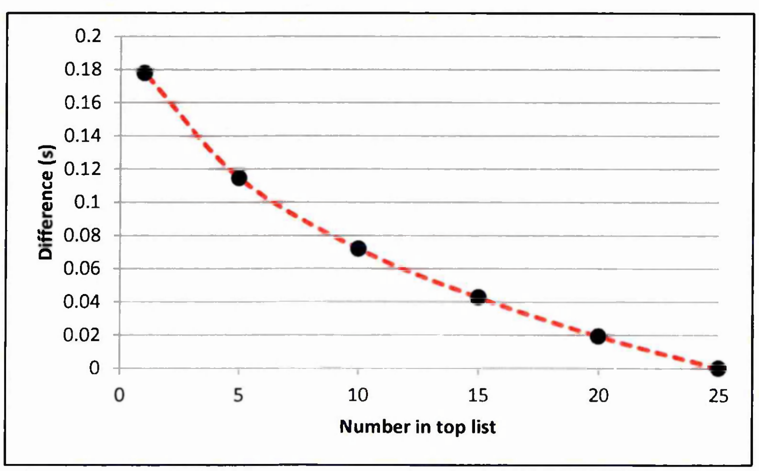


Figure 8.9: The average differences between the mean of the different top performance lists compared to the mean of the top twenty five performance list in the 100 m men's running event

The trend shown in Figure 8.9 makes it apparent that the larger the performance lists, the lower the absolute magnitude of the mean performance measure, and this difference is proportionate to the size of the performance list. As performance improvement indices are calculated from a baseline performance measure and aim to calculate performance improvements, the issues of a proportionate difference in yearly performances is not an issue. This only holds true if only the same size top lists are used, i.e. PIIs calculated with a mean of a top 3 baseline must all use mean of the top 3 data sets.

Problems are only encountered due to the variability of the data; i.e. the larger the top performance list the less influence there will be from extreme performances within the data set (as shown in chapter 3). Take for example the most extreme case, the single top performance; this data set will contain the greatest scatter as it is most influenced by one off extreme performances. On the other hand the mean of the top 25 will be least influenced by one extreme performance. Therefore it is preferable to use the largest data set available as the influence from extreme performances is reduced and data scatter is minimised. The variation between the performance improvement values calculated from 1948 using the top 25 and top 3 data for the 100 m men's running event is show in Figure 8.10.The top three has greater scatter when examining ΔPII (σ=0.07 compared to σ=0.05 for the top 25) with slightly more extreme values arising. However the overall trend is the same with an average increase between data points of 0.01 seconds.

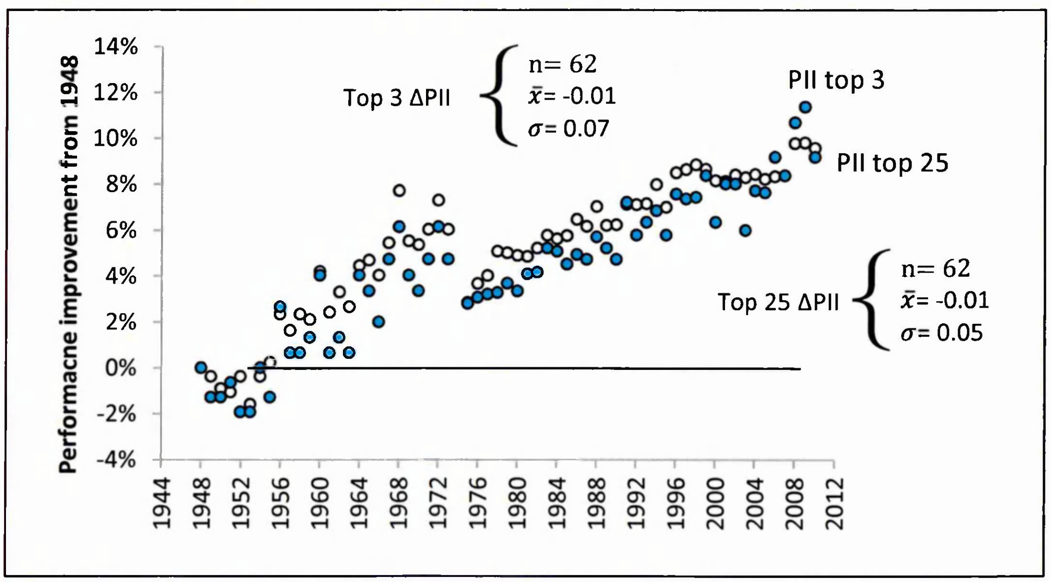


Figure 8.10: Comparison between the performance improve index values for the men's 100 m running event from 1948 to 2010 using atop 3 and a top 25 performance list.

The maximum performance improvement index values for both the data sets are shown in Table 8.1 and the difference is only 1 %.

Table 8.1: Maximum performance improvement indices for the two different data sets for the men's 100 m

Data set:	Year of maximum PII	Max PII
Mean of the top 3	2009	11 %
Mean of the top 25	2009	10 %

For the purposes of this study the magnitude of interventions in freestyle swimming will be examining using this reduced data set. It appears that by using this data set there will be little change in the magnitude of the calculated interventions or the predicted global improvement trend. However, it is believed that error values are going to be greater as data scatter is more apparent. This may make it difficult to make firm conclusions regarding the magnitudes of the various interventions.

8.6 Intervention to be modelled: Predicted interventions

The interventions that are believed to be apparent within the freestyle swimming performance improvement trends and the viability of modelling these interventions is now going to be discussed.

8.6.(a) Early interventions - tumble turns 1950s and turbulent reducing lane ropes 1966

There seems to be a large increase in freestyle swimming performances since the base line year of 1948. The performance improvements follow an exponential decay curve and as such the rate of change is greatest at the start of the curve. In the 1950s and 1960s there is a large increase in swimming performance and this could be down to external interventions or just the general global improvement factors. As such it is hard to pick out any step changes or linear uptake curves in the early stages of the development of freestyle swimming. The improvements due to the adoption of tumble turns and turbulence reducing lane ropes was treated as part of the development of the sport and accounted for within the global improvement trend.

8.6.(b) Evolution of the freestyle stroke

The freestyle stroke has evidently evolved since the base line performance figure in 1948. However any slight changes to improve stroke performance will have taken place over a number of years and each individual change will have had a minor effect on performance. Therefore it is also believed that the evolution of the freestyle stroke is too hard to quantify individually. The many small improvements in stroke technique could overall have a significant effect on performance, but difficult to isolate. Therefore the evolution of the freestyle swimming stroke was similarly treated as part of the overall global improvement trend.

8.6.(c) Fully automatic timing 1971 fully introduced

The introduction of fully automatic timing is believed to be only apparent in running events where the duration of the race is less than 60 seconds. Currently the only freestyle swimming event examined to have a completion time of less than 60 seconds is the 100 m. Therefore it is believed that fully automatic timing will only influence this event, and a step change modelling function will be implemented in the men's and women's 100 metres freestyle swimming event. Examining the available performance data it appears that fully automatic timing was used as official timing result statistic from 1971 onwards, so 1971 was the year of the step change in the 100 m freestyle event.

8.6.(d) Goggles/hats/shaving down 1970-1976

The first use of a swimming hat in elite competition occurred in 1970; therefore it is plausible that over the following years the use of swimming hats were taken up by many swimmers. Goggles also followed a similar trend for their introduction and use. Goggles were first allowed in Olympic competition in 1976, but it is feasible that their use was already becoming widespread in the years before their official introduction. Finally it is plausible that shaving down will have been adopted by swimmers in this time period, in line with the other technologies adopted to reduce a swimmer's drag. There appears to be a high level of technological developments in the early 1970s, with swimmers trying different interventions to improve performance. An increase in the rate of change of performance is evidence throughout the 1970s and can be attributed to all these technologies. It will be too difficult to separate and quantify the technology introduction of goggles, swimming hats and shaving down individually. Instead a linear uptake function from 1970 to 1976 was used to quantify all these technology advances in this time period.

8.6.(e) Changes in swimming suits

Full body swimming suits were introduced in earnest at the Sydney 2000 Olympic Games and post 2000 there appears to be an increase in swimming performance. The increase in performance could be down to the introduction of full body suits but this intervention step change occurs at the same year used to model the step change due to the formation of WADA and more organised drug testing regimes. A step change parameter in 2000 can be used to model either the drugs testing intervention or the effect of full body swimsuits. The positive or negative step parameters for the year 2000 will indicate the dominant intervention occurring in this year. If there is a negative influence on performance, it can be concluded that improved drug testing regimes are dominant. Alternatively if there is a positive effect on performance, it can be concluded that a beneficial intervention occurred possibly meaning that full body swim suits were apparent and had a positive influence on performances.

In 2008 the Speedo LZR, polyurethane swimming suit was introduced and there was an instantaneous influence upon swimming performances. Again in 2009 fully polyurethane swimming suits were introduced and another instantaneous step change in performances was apparent. In 2010 the use of both these suits were banned a rules stipulated that suits should be reverted back to earlier specifications. For the purposes of this study it is believed that swimming performance in 2010 will have reverted back to 2007 levels and follow the global improvement trend once more. A specific function was created to model the step change in 2008 and 2009, and the reversion back to the global improvement trend 2010.

8.6.(f) Drugs

The modelling of drugs was carried out using the same procedures developed for track and field athletic events. A step change in 1989 will be used to model the instantaneous effect of random out of competition drug testing. Again in 2000 a step change will be used to model the effect the formation of WADA and more organised drug testing regimes and procedures. As mentioned earlier, the nature of the step change parameters in 2000 will used to determine whether there is a positive or negative intervention occurring, hence whether a drugs or swim suit effect is present.

A linear uptake of drugs was modelled with two different start years: 1968 and 1975. The start year that gave the best fit was then used at the start year in the linear uptake and decline model. There were not clear years where swimming performances appear to have prematurely peaked. Therefore a peak year of 1988 was chosen for the end of the linear uptake and 1999 was chosen as the end year of the linear decline, this was in line with the fitting of drugs intervention developed for running.

8.7 Improvement function generation steps

The intervention modelling steps used to optimise the improvement function for all freestyle swimming events has been summarised in Table 7.4.

Table 8.2: Improvement function generation steps for the men's and women's long course freestyle swimming events

Step no.	Intervention modelled:	Model description:	IF GUI model no.
1	Global improvement	Global improvement trend	2
2	Full body polyurethane suit introduction	Step change 2008, 2009 and 2010 back to global improvement trend	39
3	Uptake of swimming goggles and hats 1970 - 1976	Exp + swimsuits + Lin uptake	123
4	Fully automatic timing 1971	Exp + swimsuits + Lin uptake + 1 step	124
5	Drug testing step change 1989	Exp + swimsuits + Lin uptake + 2 steps	125
6	Drug testing/full body suits step change 2000	Exp + swimsuits + Lin uptake + 3 step	126
7	Drugs linear uptake 1	Exp + swimsuits + Lin uptake + 2 step + Drugs uptake (1975 -1988)	127
8	Drugs linear uptake 2	Exp + swimsuits + Lin uptake + 2 step + Drugs uptake (1968-1988)	127
9	Drugs linear uptake and decline (best start date)	Exp + swimsuits + 2 Lin uptake + 2 step + Drugs uptake and decline (xxxx-1988-2000)	128
10	Drugs linear uptake and decline and Olympics	Periodic function of four years from 1948	129

8.8 Results – graphical representation and goodness of fit

The change in goodness of fit values (adjusted regression coefficient) has been plotted for each fitting step of improvement function to men's and women's freestyle events in Figure 6.26.

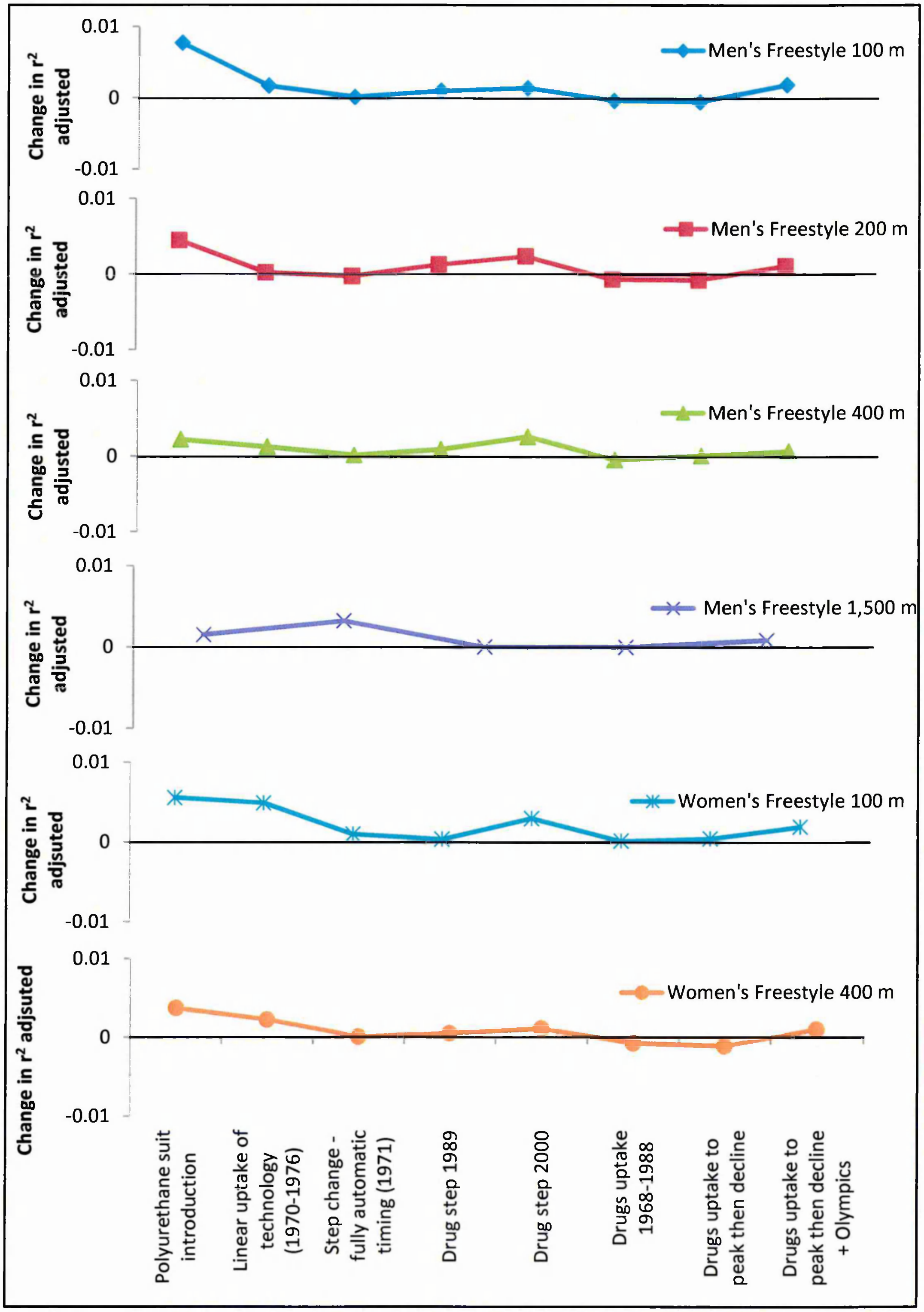


Figure 8.11: Change in adjusted regression coefficient for the modelling steps men's and women's freestyle swimming events

Any unexpected parameter values found during the fitting procedure for all freestyle swimming events have been noted and displayed in Table 6.6. It appears all swimming freestyle events did not adhere to a drop in performance in 2000 due to the formation of WADA. Instead a positive step change parameter was found in 2000 and is indicative of a positive influence factor such as the introduction of full body swim suits.

Table 8.3: Interventions for the different events that have been excluded from the final improvement function model as unexpected parameters were found

Event	Modelling step/ intervention	Reason for omitting from final model
Events of greater than 100 m	Fully automatic timing	Very large confidence intervals found on step change parameter
All events	Drug step change 2000	Positive effect found
1,500 m men and 100 m women	Drug step change 1989	Positive effect found
1,500 m men and 100 m women	Drugs uptake	Negative effect found
400 m and 1,500 m men and 100 m women	Drugs uptake and decline	Negative effect found

Taking into account which improvement function fitting steps showed an improvement in fit as well as the unexpected parameters found, the final improvement models tailored for each swimming event are shown below in Table 6.7. It appears that no linear uptake or decline of drugs could be found, and only a 1989 step change parameter accounting for a drug testing interventions was found in all events.

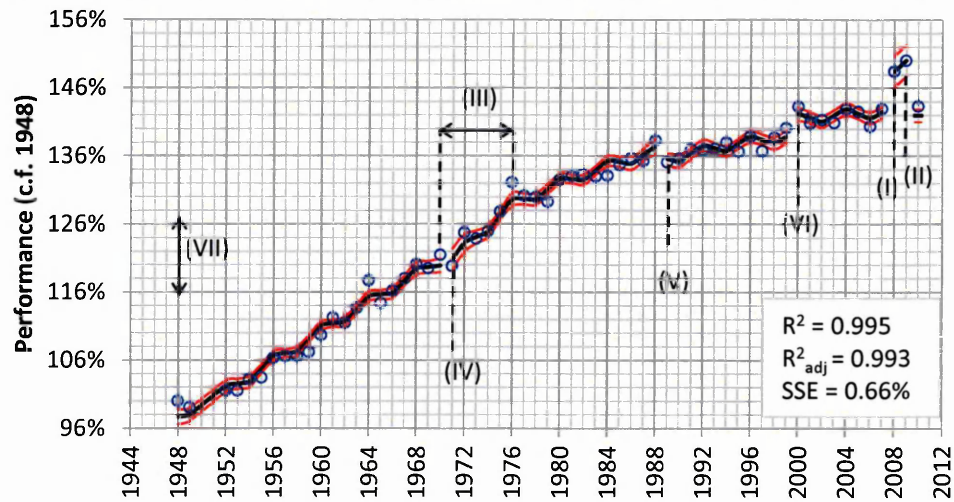
Table 8.4: Final improvement function model and GUI assigned model number, customised for each event

Event	Model description	Model type	GUI IF No.
Men's 100 m freestyle	Polyurethane suits + linear uptake of technology (1970-1976) +FAT (1971) + 1989 drug intervention+ 2000 full body suit intervention + Olympics	Expo + linear uptake +3 step interventions +Olympics	130
Women's 100 m freestyle	Polyurethane suits + linear uptake of technology (1970-1976) +FAT (1971) + 2000 full body suit intervention + Olympics	Expo + linear uptake +2 step interventions +Olympics	131
Men's and women's freestyle events greater than 100 m	Polyurethane suits + linear uptake of technology (1970-1976) + 1989 drug intervention+ 2000 full body suit intervention + Olympics	Expo + linear uptake +2 step interventions +Olympics	131
Men's 1,500 m	Polyurethane suits + linear uptake of technology (1970-1976) + 1989 drug intervention+ 2000 full body suit intervention + Olympics	Expo + linear uptake +1 step intervention +Olympics	134

8.9 Final improvement models – long course speed skating events

The final improvement functions models for all the long course freestyle swimming events examined have been represented graphically from Figure 8.12 to Figure 8.17. Each intervention accounted for within the final improvement function has also been labelled and the size of the different parameters summarised.

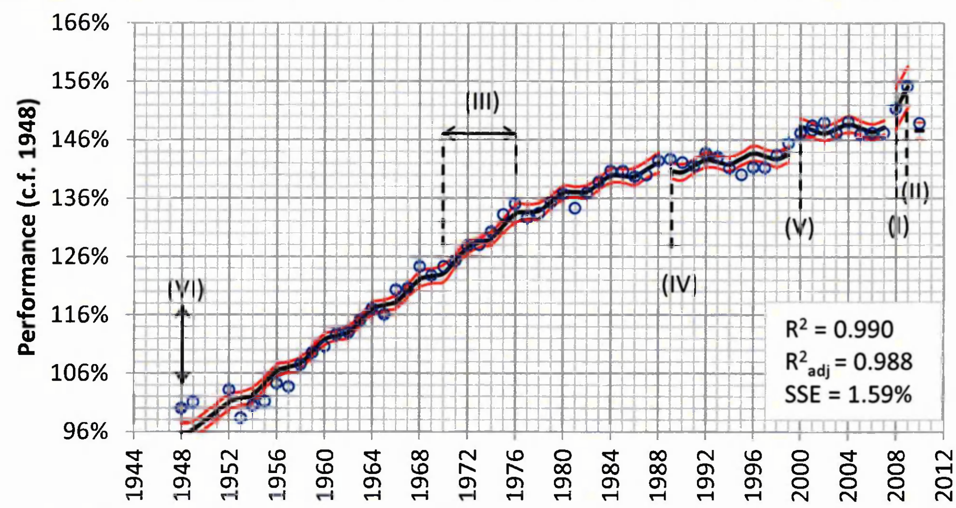
Men's 100 m freestyle long course



	Intervention	Parameters
	Global improvement	L=139.62% (± 4.77); a=0.0095 (± 0.003353); b=20.9231 (± 4.75)
I	Polyurethane panelled swimming suits	k_1=103.57% (± 1.73); k_1year=2008 (from global)
II	Full polyurethane swimming suits	k_2=104.29%; k_2year=2009 (from global)
III	Linear uptake of body-shaving, goggles and swimming hats	LU=0.75%yr^{-1} (± 0.47); LU_{peak}=4.51% (± 2.81); LU_{start}=1970; LU_{end}=1976
IV	Fully automatic timing	k_3=98.73% (± 1.74); k_3year=1971
V	Stricter drug testing	k_4=98.83% (± 1.28); k_4year=1989
VI	Use of full body swimming suits	k_5=101.73% (± 1.06); k_5year=2000
VII	Olympic Games	Amp, A=0.76% (± 0.42); R^2=0.995; R^2_{adj}=0.993; MSE =0.01%; SSE=0.66%

Figure 8.12: Final improvement function model for the men's 100 m freestyle event

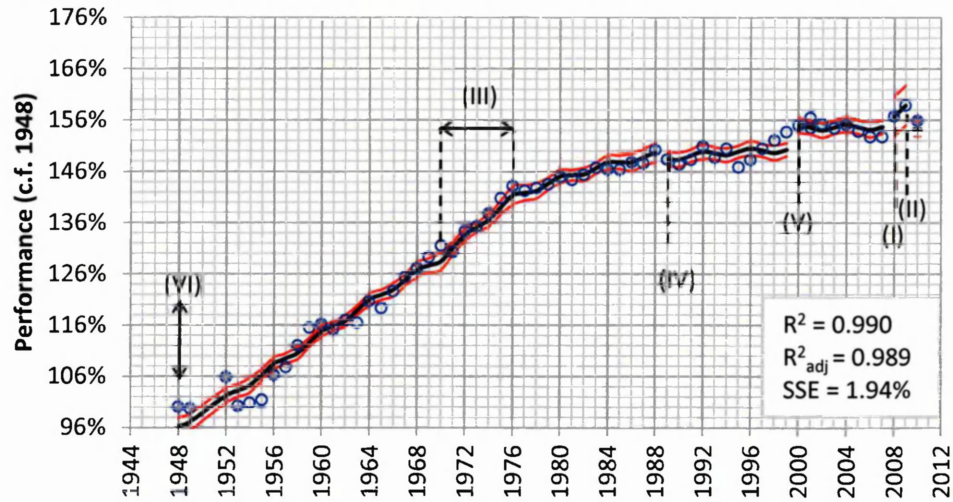
Men's 200 m freestyle long course



	Intervention	Parameters
	Global improvement	L=143.30% (± 6.41); a=0.003167 (± 0.001668); b=39.4444 (± 12.48)
I	Polyurethane panelled swimming suits	k_1=101.62% (± 2.54); $k_1 year$=2008 (from global)
II	Full polyurethane swimming suits	k_2=104.63% (± 2.51); $k_2 year$=2009 (from global)
III	Linear uptake of body-shaving, goggles and swimming hats	LU=0.40%yr^{-1} (± 0.53); LU_{peak}=2.39% (± 3.19); LU_{start}=1970; LU_{end}=1976
IV	Stricter drug testing	k_3=99.15% (± 1.91); $k_3 year$=1989
V	Use of full body swimming suits	k_4=102.70% (± 1.39); $k_4 year$=2000
VI	Olympic Games	Amp, A=0.69% (± 0.64)
		R^2=0.990; R^2_{adj}=0.988; MSE =0.03%; SSE=1.59%

Figure 8.13: Final improvement function model for the men's 200 m freestyle event

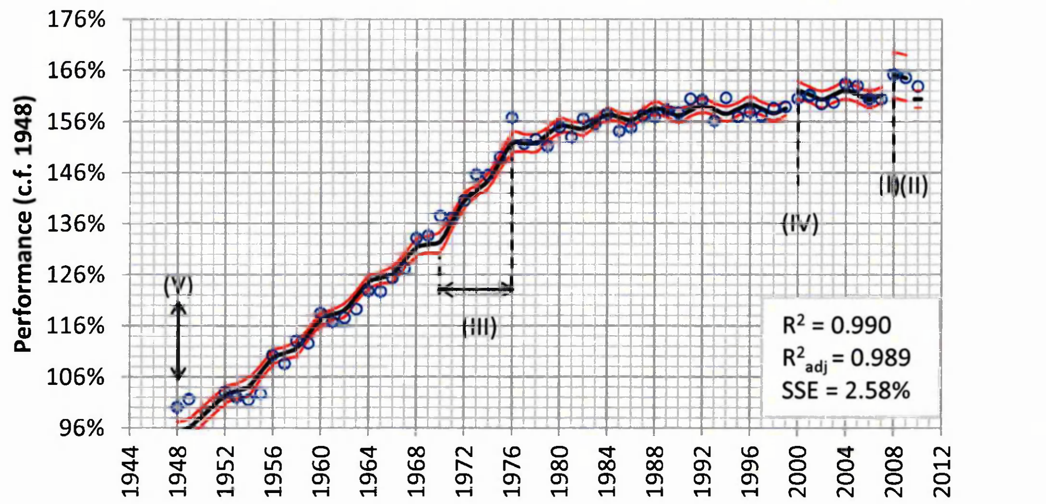
Men's 400 m freestyle long course



	Intervention	Parameters
	Global improvement	*L*=146.80% (± 2.54); *a*=0.001161 (± 0.0006839); *b*=73.3897 (± 25.79)
I	Polyurethane panelled swimming suits	k_1=100.95% (± 2.69); k_1year=2008 (from global)
II	Full polyurethane swimming suits	k_2=102.70% (± 2.65); k_2year=2009 (from global)
III	Linear uptake of body-shaving, goggles and swimming hats	LU=0.79%yr^{-1} (± 2.54); LU_{peak}= 4.76% (± 3.79); LU_{start}=1970; LU_{end}=1976
IV	Stricter drug testing	k_3=99.32% (± 1.91); k_3year=1989
V	Use of full body swimming suits	k_4=102.80% (± 1.29); k_4year=2000
VI	Olympic Games	Amp, *A*=0.53% (± 0.71)
		R^2=0.990; R^2_{adj}=0.989; *MSE* =0.04%; *SSE*=1.94%

Figure 8.14: Final improvement function model for the men's 400 m freestyle event

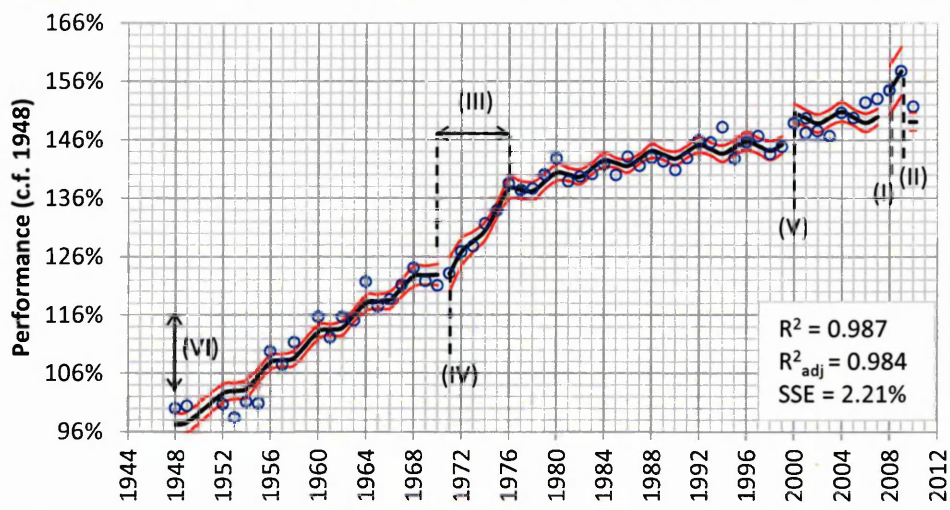
Men's 1500 m freestyle long course



	Intervention	Parameters
	Global improvement	L=148.68% (± 4.83); a=0.0003133 (± 0.0002141); b=167.0197 (± 65.30)
I	Polyurethane panelled swimming suits	k_1=101.83% (± 2.97); k_1year=2008 (from global)
II	Full polyurethane swimming suits	k_2=102.03% (± 2.93); k_2year=2009 (from global)
III	Linear uptake of body-shaving, goggles and swimming hats	$LU=1.65\%yr^{-1}$ (± 0.70); LU_{peak}=9.90% (±4.19); LU_{start}=1970; LU_{end}=1976
IV	Use of full body swimming suits	k_4=101.69% (± 1.27); k_4year=2000
V	Olympic Games	Amp, A=0.90% (± 0.84)
		R^2=0.990; R^2_{adj}=0.989; MSE =0.05%; SSE=2.58%

Figure 8.15: Final improvement function model for the men's 1500 m freestyle event

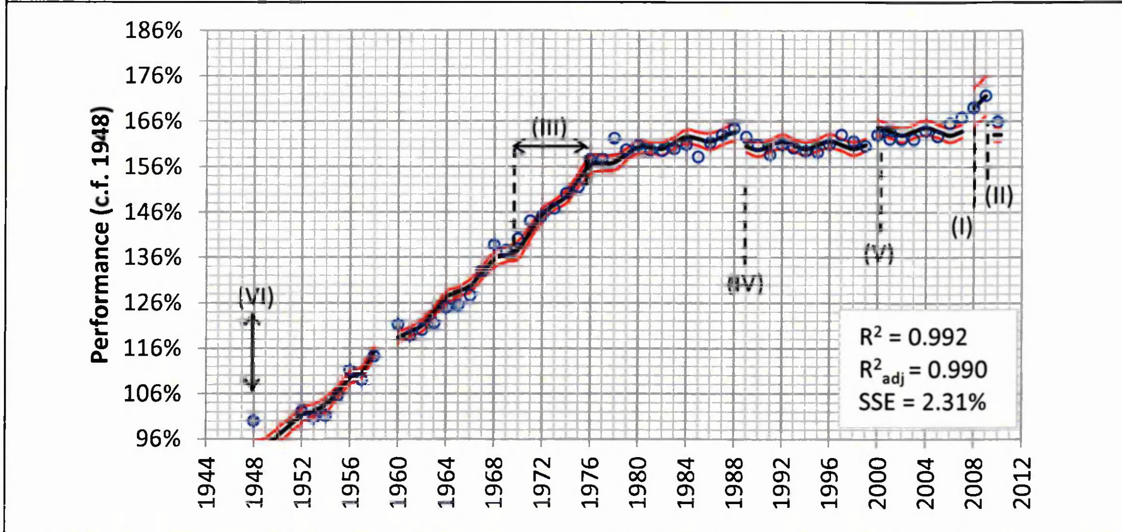
Women's 100 m freestyle long course



	Intervention	Parameters
	Global improvement	L=138.47% (± 4.42); a=0.003972 (± 0.002554); b=37.9448 (± 14.64);
I	Polyurethane pannelled swimming suits	k_1=102.36% (± 2.99); k_1year=2008 (from global)
II	Full polyurethane swimming suits	k_2=105.19% (± 2.94); k_2year=2009 (from global)
III	Linear uptake of body-shaving, goggles and swimming hats	LU=1.92%yr^{-1} (± 0.87); LU_{peak}=11.54% (± 5.22); LU_{start}=1970; LU_{end}=1976
IV	Fully automatic timing	k_3=97.05% (± 3.12); k_3year=1971
V	Use of full body swimming suits	k_5=103.04% (± 1.51); k_5year=2000
VI	Olympic Games	Amp, A=0.93% (± 0.77)
		R^2=0.987; R^2_{adj}=0.984; MSE =0.04%; SSE=2.21%

Figure 8.16: Final improvement function model for the women's 100 m freestyle event

Women's 400 m freestyle long course



	Intervention	Parameters
	Global improvement	L=155.46% (± 6.45); a=0.00005758 (± 0.00004394); b=437.4730 (± 185.01)
I	Polyurethane pannelled swimming suits	k_1=102.65% (± 2.80) ; k_1year=2008 (from global)
II	Full polyurethane swimming suits	k_2=104.75% (± 2.76); k_2year=2009 (from global)
III	Linear uptake of body-shaving, goggles and swimming hats	LU=1.31%yr^{-1} (±0.83); LU_{peak}=7.88% (± 5.01); LU_{start}=1970; LU_{end}=1976
IV	Stricter drug testing	k_3=98.49% (± 1.51); k_3year=1989
V	Use of full body swimming suits	k_4=101.85% (± 1.21); k_4year=2000
VI	Olympic Games	Amp, A=0.86% (± 0.81)
		R^2=0.992; R^2_{adj}=0.990; MSE =0.05%; SSE=2.31%

Figure 8.17: Final improvement function model for the women's 400 m freestyle event

8.10 Results - Interventions modelled

8.10.(a) Suit intervention step changes

8.10.a.(i) Results – full body suits

The first intervention to be examined is the effect of the various evolutionary stages of the full body swimming suit. Firstly in 2000 the introduction of full body suits deemed to reduce drag on a swimmer was unintentionally modelled when trying to examine for a drugs testing intervention effect. In 2008 and 2009 a specific model function was used to model the step changes in the two years due to the introduction of Polyurethane materials in suit design. For each freestyle swimming event the size of influence of the different suits in terms of percentage increase and drop in raw performance time is shown in Table 8.5 and graphically in Figure 8.18

Table 8.5: The magnitude of the step changes accounting for the various evolutionary stages of the full body suit for each different freestyle swimming event

	2000				2008				2009			
	Step change (PII)	+/-	Step change (s)	+/-	Step change (PII)	+/-	Step change (s)	+/-	Step change (PII)	+/-	Step change (s)	+/-
Men 100 m	1.73%	1.06	-0.47	0.27	3.57%	1.73	-1.02	0.49	5.18%	1.71	-1.47	0.48
Men 200 m	2.70%	1.39	-1.38	0.84	1.62%	2.54	-1.04	1.62	4.63%	2.52	-2.94	1.58
Men 400 m	2.80%	1.29	-0.47	0.27	0.95%	2.69	-1.32	3.72	2.70%	2.65	-3.73	3.64
Men 1,500 m	1.69%	1.27	-7.59	7.71	1.83%	2.97	-10.28	16.66	2.03%	2.93	-11.41	16.39
Women 100 m	3.04%	1.51	-1.00	0.49	2.36%	2.99	-0.77	0.97	5.19%	2.95	-1.69	0.95
Women 400 m	1.85%	1.21	-2.90	1.88	2.65%	2.80	-4.14	4.35	4.75%	2.76	-7.39	4.25
Mean	2.30%		-2.62		2.16%		-3.10		4.08%		-4.77	2.30%

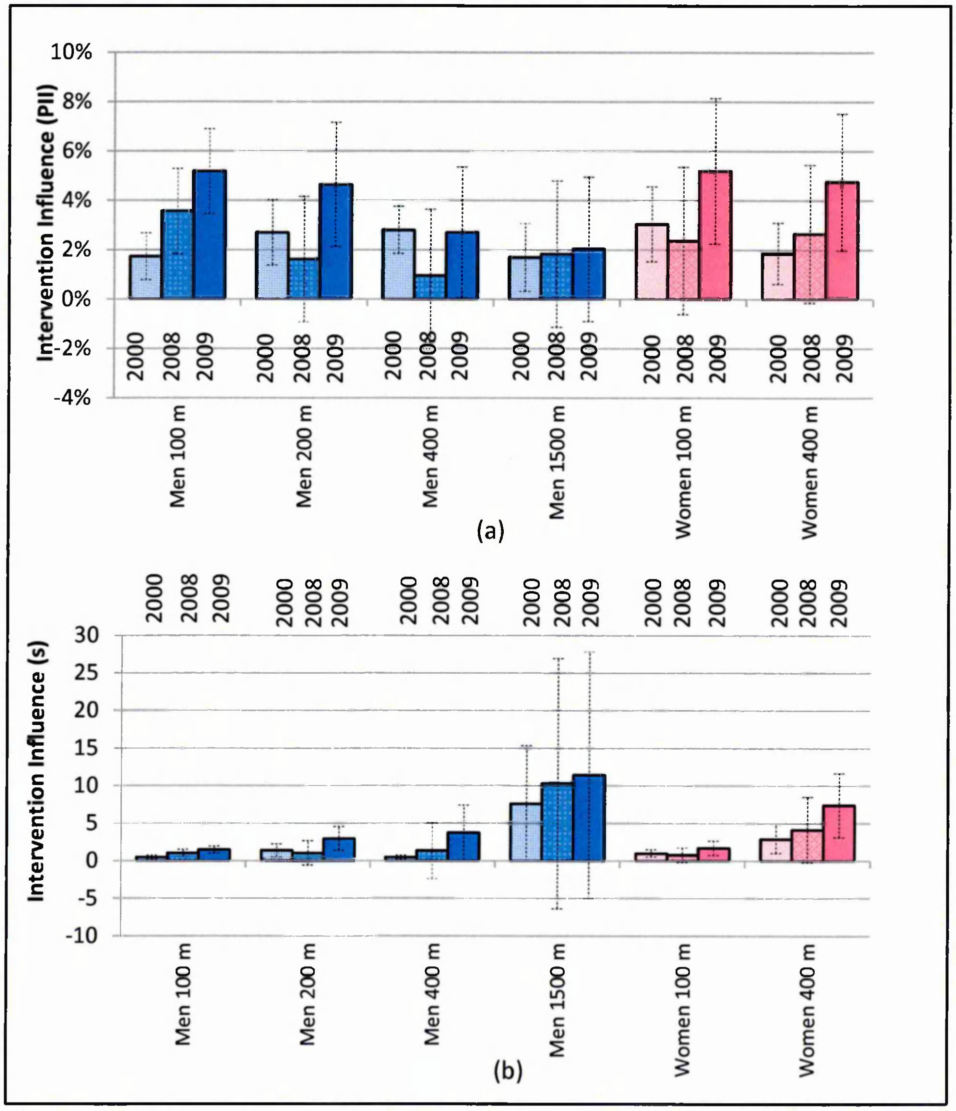


Figure 8.18: The magnitude of the step changes accounting for the various evolutionary stages of the full body suit for each different freestyle swimming event shown in units of (a) percentage improvement in the performance improvement index and (b) reduction of race time in seconds

8.10.a.(ii) Discussion – full body suits

Introduction of fully body suits in 2000

The introduction of full body suits in 2000 was inadvertently modelled with a step change which was originally used to account for the formation of WADA and better drug testing regimes. The positive step change found is indicative of an intervention which has a beneficial influence on swimming performance. This intervention has been attributed to the introduction of drag reducing fabrics and full body swim suits. The formation of WADA could have had a negative influence on swimming performances, but this negative effect may have been obscured by the positive influence from the first generation full body swimming suits. This means the actual magnitude of the effect of the first full body swim suits may have been higher than that modelled here.

The step change in 2000 accounting for the introduction of full body suits is similar for all men's and women's freestyle events, with a maximum effect seen in the women's 100 m at 3.04 (+/-1.51) % and lowest in the men's 1500 m, at 1.69 (+/-1.27) %. The average influence for the 2000 full body suits is 2.30 % and at first glance, appears to be more than the 2008 swimming suit influence, but lower than the 2009 suit influence.

There appears to be a large confidence interval for the men's 1500 m event, but these values are not greater than the modelled influence. This means that a positive effect from the 2000 suits is more than likely in the men's '1500 m event.

Introduction of polyurethane panelled body suits 2008

The introduction of polyurethane panelled body suits (Speedo LZR suit) had an average positive influence of 2.16 %, and appears to be lowest out of the three suit interventions. The greatest influence appeared to be in the men's 100 m event at 3.57 (+/- 1.73) %. The confidence region for all bar one event; the 100 m men's freestyle event were larger than the modelled effect, so it hard to say that there is an actual effect arising from the introduction of the initial polyurethane panelled swim suit. As 2008 is also an Olympic year, it makes it difficult to distinguish between the positive effects from the Polyurethane suit and the Olympics Games, and results in large error bounds. The 100 m men's freestyle event is the only event where a definite positive effect from the 2008 polyurethane panelled swim suit is apparent.

Introduction of full polyurethane body suits 2009

The influence of fully body polyurethane body suits had an average influence across all freestyle swimming events of 4.08 %. The average error was +/- 2.59 % and is less than the measured average influence, which means a definite positive effect from the

2009 swim suits is apparent in the majority of events. The men's 1500 m was the only freestyle swimming event that hard a larger confidence bound than the measured influence, which meant a positive 2009 swim suit effect is questionable. The effect of the 2009 swim suits is the greatest for all of the modelled changes in swim suit, and is feasibly down to latest generation of full body suits having the lowest hydrodynamic drag. This is plausible as the latest suits did not contain any conventional fabrics which contributed to drag.

The banning of all non-fabric and complete covering suits in 2010 saw a drop of performance levels which back to levels of pre 2008 and was assumed to be on par to the natural evolution of swimming events. It is also believed that the influence of swimming suits was on the same level seen after the introduction of drag reducing fabrics with the first full body suit introduction in 2000.

More influence from full body suits in the shorter event distance

It appears that the there is a general trend apparent concerning the influence of all full body swimming suit introduction; the shorter the race distance the greater the influence from each individual swim suit. This could be due to the increased speed of the shorter distance freestyle events, the relationship between event distance and average speed for 2010 performances is shown in Figure 8.8.

Equation 47 shows the relationship between drag force F_d and the velocity v. A is the projected frontal area, ρ is the density of the water and C_d is the drag coefficient.

$$F_d = \frac{1}{2}\rho A C_d v^2 \tag{47}$$

Assuming that the coefficient of drag, C_d and frontal area, A are constant as velocity increases as does the drag force in a squared relationship. This relationship is shown graphically in Figure 8.19.

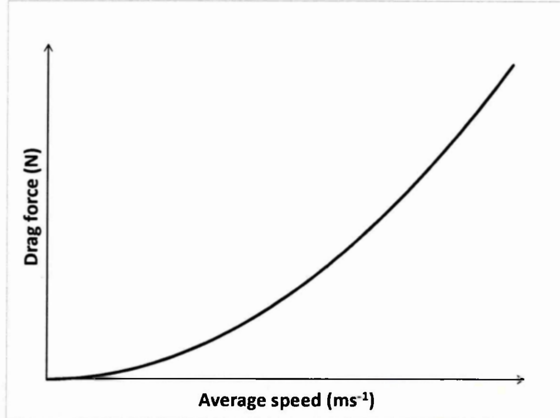


Figure 8.19: Relationship between drag force and speed, given ρ AC_d is constant

Assuming that the water density ρ stays constant and the introduction of a full body swim suit reduces AC_d, this would reduce the drag force experienced at various swimming speeds. This relationship is shown in Figure 8.22.

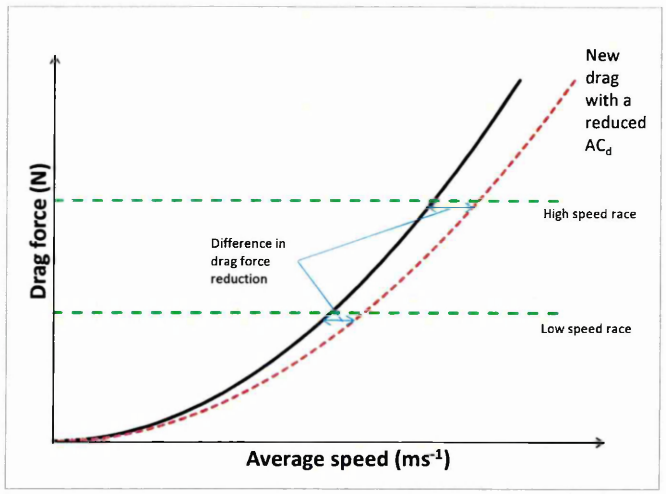
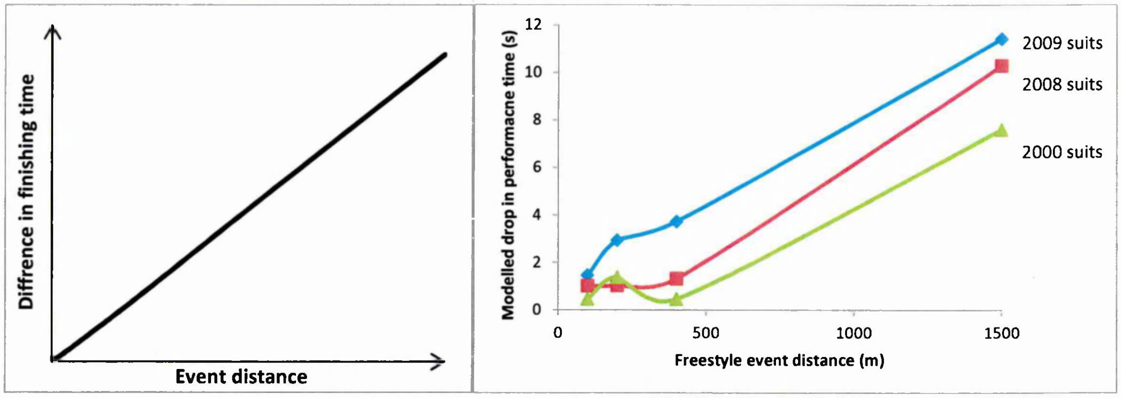


Figure 8.20: Relationship between drag force and speed, shown for a constant AC_d and for a reduced lowered AC_d.

At a constant speed, the drag acting on a swimmer is exactly equal to the propulsive force a swimmer is producing. If the propulsive force that swimmer can produce for the various swimming events is assumed to remain constant, the reduction in drag force when using a new suit shown in Figure 8.22 , would in turn mean that the speed of the swimmer will increase and hence a lower race time will be apparent. As the increase in speed will be proportionate to the original speed, finishing times will be reduced proportionally and hence the drop in race times will follow a linear trend like that shown in Figure 8.21 (a). With the modelled drop in performance times for the different freestyle event distances they loosely appears to follow this same linear trend (Figure 8.21 (b)) however more data points or races distances are required to see if this trend is accurate for the different suit interventions.



(a) (b)

Figure 8.21: (a) Relationship between event distance and reduction in finishing time (b) Relationship between event distance and modelled reduction in finishing time for the various suit interventions

High error bounds with step change parameters

The high error bounds calculated for the step change parameters accounting for all the changes in full body swimming suits can be attributed to the reduced size of the performance data lists. Error values in the step change parameters could be reduced with more data post 2010 and an expanded data set. Ideally a yearly top 25 performance data set is required to examine the step changes in more detail. As mentioned earlier, unfortunately the only data sets available going back to 1948 is the top 3 ranked performances in the long course freestyle event.

8.10.a.(iii) Conclusion – full body suits

The introduction of full body suits from the development of low drag fabrics in 2000 has appeared to positively influence freestyle swimming performance. Again in 2008 the introduction of polyurethane panelled full body suits had a positive effect on swimming performance. Finally in 2009 the introduction of full polyurethane swimming suits also had a positive influence on swimming performances. In 2010 a rule change dictated that non fabric suits as well as the full covering nature of the suits were to be banned from then onwards. Suit development was regressed back to using drag reducing fabrics first seen in 2000 with the first generation of full body swimming suits. This means that any performances gained with the 2008 and 2009 step changes are now void as the suits are now been banned.

The greatest performance gains seen from the development of full body suits is down to the 2009 introduction of full polyurethane suits. The next greatest level of performance development came from the in 2000 with the introduction of fabrics claimed to have lower drag characteristics than shaved skin. The lowest apparent intervention from suit introduction was from the 2008 full body suits, however the full extent of this intervention may have been masked by an Olympic intervention year.

The magnitude of the effect of the different swim suits for the different freestyle distances appears to follow a linear trend, however the actual magnitude of the influence of swim suit is hard to ascertain as the confidence intervals are so high and this is attributed to the reduced performance data set available for freestyle swimming from 1948.

8.10.(b) Linear uptake of technology, goggles hats and shaving down

8.10.b.(i) Results – Linear uptake of technology

The next intervention modelled was the linear uptake of technology in swimming from 1970 to 1976. The linear uptake of technology in swimming within this time period incorporates various technologies, such as the uptake of shaving down, and the use of goggles and swimming hats. The effect of these three technologies could not be individually quantified and have therefore been modelled by using a single linear uptake model. The peak influence of the linear uptake model for each freestyle swimming event examined is shown in Table 8.6 and represented graphically in Figure 8.22.

Table 8.6: The magnitude of the linear uptake accounting for the various technologies taken up in the 1970s (goggles, swimming hats and shaving down) for each different swimming event

	Event	Linear peak (PII %)	+/-	Linear peak (s)	+/-
Men	100 m	4.51%	2.81%	1.28	0.79
	200 m	2.39%	3.19%	1.52	2.03
	400 m	4.76%	3.79%	6.55	5.16
	1,500 m	9.90%	4.19%	54.67	22.63
Women	100 m	11.54%	5.22%	3.70	1.63
	400 m	7.88%	5.01%	12.17	7.59

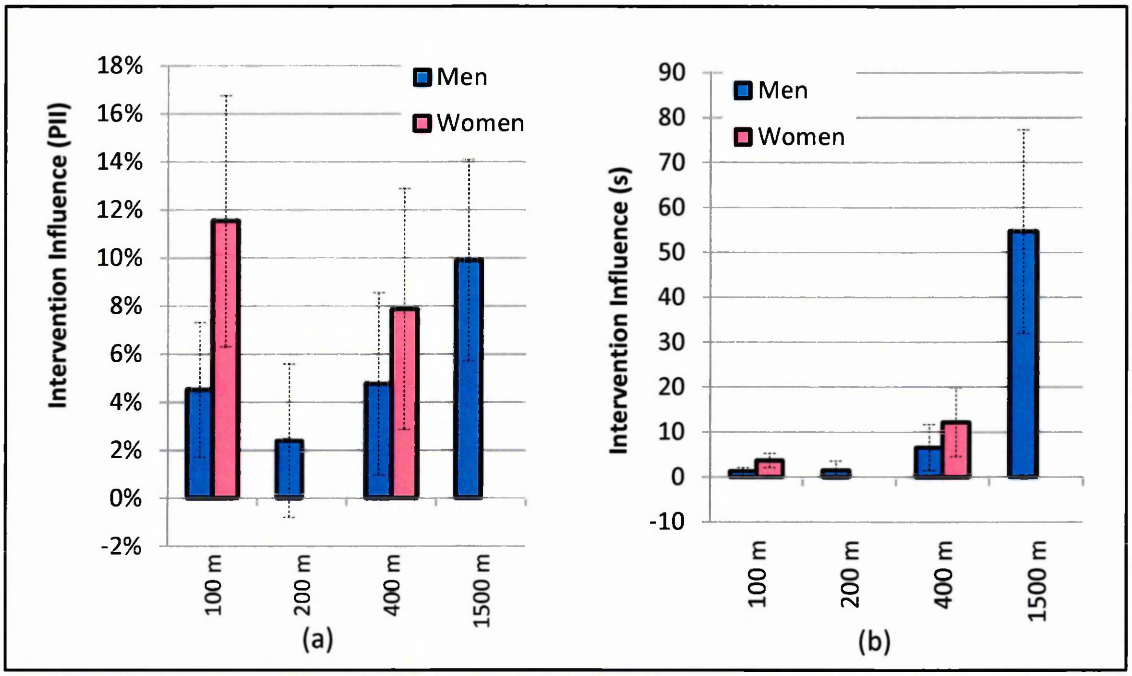


Figure 8.22: The magnitude of the linear uptake accounting for the various technologies taken up in the 1970s (goggles, swimming hats and shaving down) for each different freestyle swimming event shown in units of (a) percentage improvement in the performance improvement index and (b) reduction of race time in seconds

8.10.b.(ii) Discussion – Linear uptake of technology

The linear uptake model attempts to measure the influence of three different technology uptakes in the 1970s and as such it is difficult to say exactly what intervention has been gauged. The largest magnitude of influence seen using the linear uptake model was in the women's 100 m freestyle event, with a performance improvement of 11.54 (+/-5.22) % equating to an actual time drop of -3.70 (+/-1.63) seconds. The women's freestyle 100 m event may have seen the largest improvement from the technology introduced throughout the 1970s for one dominant reason. As women generally have longer hair than men, they conceivably will experience a greater level of drag when not using a swimming hat. When swimming hats were introduced, they were more beneficial in women's events as they reduced drag to a greater extent when compared to the corresponding men's events. Within the women's events examined for this study the introduction of drag reducing technologies such as shaving down and swimming hats are likely to be more prominent than the adoption of goggles.

It also appears that the technology introduction was more beneficial in the shorter women's freestyle event examined, the 100 m. This may be because any reduction in drag that was brought about by swimming hats as well as shaving down influenced the higher speed events to a greater extent.

On the other hand the 1500 m men's event appeared to be influenced the most from the technology uptake in the 1970s. The drag reduction technologies, swimming hats and shaving down may not have been as influential in the men's events as the women's. Improvements in swimming performance in the men's event may have been driven by another technology, the uptake of goggles. The increased training time that came about from the introduction of goggles may have allowed long distance swimmers to train for longer, increasing their endurance capabilities and thus increasing the performance in the longer distance even the most significantly. For men's freestyle swimming goggles technologies is plausibly the dominant technology introduced in the 1970s.

8.10.b.(iii) Conclusion – Linear uptake of technology

The linear uptake of technology in the men's freestyle event influenced the 1500 m event the greatest, and is attributed to the increase in training time and subsequent endurance capabilities the male athletes gained with the introduction of goggles. Within the women's freestyle events, the 100 m was influenced the most from the linear uptake of technology. The dominate factor which is believed to influence this improvement in the women's events is down to the drag reduction the introduction of swimming hat brought about. The large error bounds in the linear peak term for the men's 200 m make it difficult to say that there is a linear effect occurring in this event. In spite of this all other events appear to experience a positive effect from the linear uptake of technology in the 1970s when accounting for the error bounds.

8.10.(c) Fully automatic timing introduction

8.10.c.(i) Results – Fully automatic timing

The step change parameters found that accounts for the introduction of fully automatic timing in 1971 for the 100 m freestyle swimming events are shown in Table 8.7 and graphically in Figure 8.23.

Table 8.7: The magnitude of the step changes accounting for the introduction of fully automatic timing in the 100 m men's and women's freestyle swimming event

Gender	Event	Intervention size (PII %)	+/-	Intervention size (s)	+/-
Men	100 m	-1.27%	1.74%	0.37	0.51
Women	100 m	-2.95%	3.12%	0.98	1.04

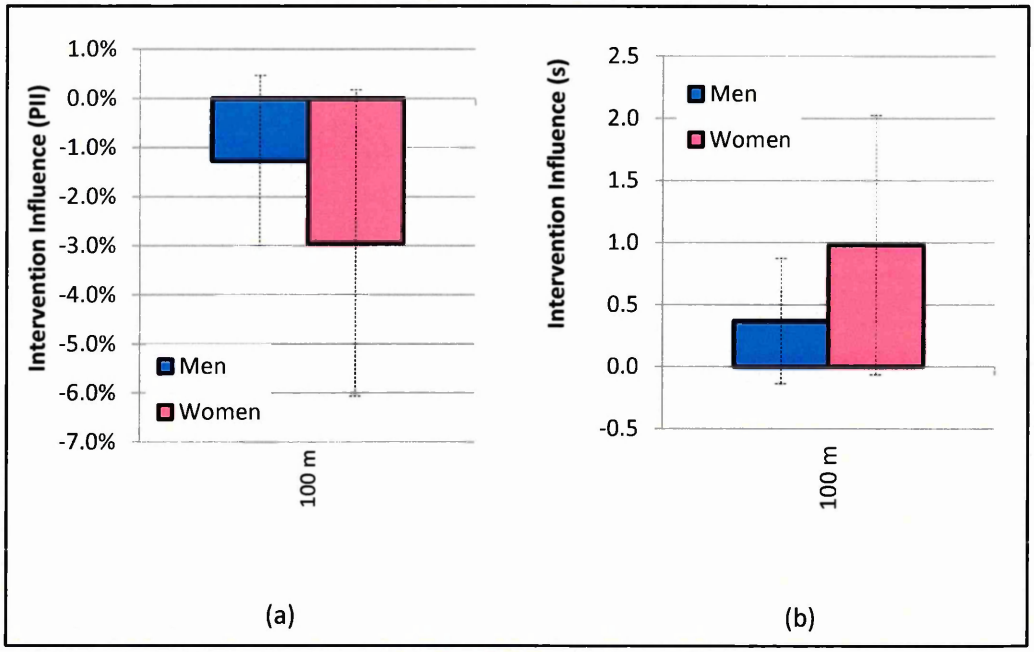


Figure 8.23: The magnitude of the step changes accounting for the introduction of fully automatic timing in the 100 m men's and women's freestyle swimming event shown in units of (a) percentage improvement in the performance improvement index and (b) reduction of race time in seconds

8.10.c.(ii) Discussion – Fully automatic timing

The step change parameter used to account for the introduction of fully automatic timing in swimming contains large error bounds. This makes it difficult to pin point the size of the detrimental effect of fully automatic timing swimming. However the effect of fully automatic timing in swimming events appears to be generally greater than the effect found in running events. This could be because it is more difficult to judge the finish of a swimming race as a judge has to interpret the exact point where a swimmer touches the wall to end the race. As it is difficult to see underwater and see the exact finishing point of a swimming race when a swimmer touches a wall, it is plausible that a judge will prejudge the finish of the race to a greater extent than in running. The reaction time of a timing official at the start of a swimming race will most likely be the same as a running timing official so no apparent gains in performance times will be encountered here.

The common theme with the swimming performance data examined so far is the large 95 % confidence bounds found for all parameters. This is likely due to the increased scatter of data found through using the mean of the top three performance data sets. This is so far making it hard to make firm conclusion on the influence of various interventions.

8.10.c.(iii) Conclusion – Fully automatic timing

Fully automatic timing appears to be apparent in the 100 m men's and women's freestyle event. The error bounds found for the fully automatic timing parameters are high which makes it difficult to quantify the actual effect of fully automatic timing. The magnitude of the FAT effect is similar to that seen in the running sprinting events, but are generally higher in swimming. Judging of a finish in a swimming race is more difficult as the timing official has to judge when the swimmer touches the wall underwater. This may lead to a higher FAT parameter as timing officials may be inclined to prejudge the finish of a race to a greater extent.

8.10.(d) Drugs intervention 1989

8.10.d.(i) Results – Drugs intervention 1989

The only drugs intervention that was apparent in swimming events was the step change to account for the introduction of random out of competition drugs testing in 1989. It is plausible that performance-enhancing drugs did not influence swimming events to such extent as witness in the previously examined events, meaning their influence could not be measured using the developed methods. Shown in Table 8.8 are the magnitudes of the step change factor used to gauge the influence of drug testing procedures introduced in 1989, these values are shown graphically in Figure 8.24.

Table 8.8: The magnitude of the effect of the introduction of drug testing intervention in 1989 for each different swimming event

Gender	Event	Intervention size (PII %)	+/-	Intervention size (s)	+/-
Men	100 m	1.17%	1.28%	0.34	0.37
	200 m	0.85%	1.91%	0.55	1.23
	400 m	0.68%	1.91%	0.95	2.67
Women	400 m	1.51%	1.51%	2.39	2.39

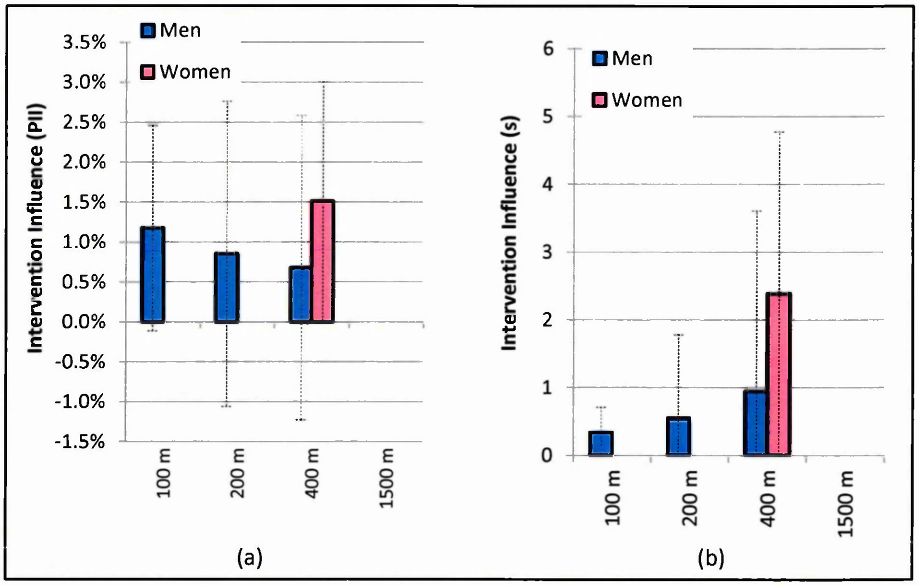


Figure 8.24: The magnitude of the effect of the introduction of drug testing intervention in 1989 for each different freestyle swimming event shown in units of (a) percentage improvement in the performance improvement index and (b) increase in race time in seconds

8.10.d.(ii) Discussion – Drugs intervention 1989

The only drugs model to account for any performance-enhancing drugs in freestyle swimming performance was the step change intervention in 1989 used to model the effect of the introduction of out of season random drug testing on athletes. None of the other models developed to account for the use of performance-enhancing drugs were not successfully applied, and suggests that swimming performances are to a lesser degree influenced by drugs. Additionally the confidence intervals for the step change parameter are very high, which makes it difficult to say whether there is a step change due to a drug testing intervention at all.

Across all events the size of the 1989 step change was also found to be very small, between 0.68 (+/-1.91) % in the men's 400 m to 1.51 (+/-1.51) % influence in the women's 400 m. The reduced size of the data top performers set is thought not to have influenced the modelled size of the influence. The top three performers would show a clear increase or decrease in performance due to drugs, just like the larger performance data sets. The only problem in examining for a drugs effect is from scatter in the data as a result of the data set. The scatter in the data could mask the step change due to the introduction of drug testing procedures and is believed to be what creates that large error bounds found in the step change parameters.

Women's freestyle swimming performance does not follow the same development trend seen in the other athletic events examined so far. Visually there are no peaks in performances during the 1980s. Instead a slight peak in performance is seen in between 1978 and 1980. This period is directly after the linear uptake of technology throughout the 1970s and could be due to a different intervention step change that has not been accounted for. Drug testing interventions in swimming could possibly have not followed the same pattern as in other athletic events, and drugs influenced peaks years may have occurred earlier. Drug testing interventions may have been introduced earlier and been more widespread in swimming when compared to track and field athletics. One other possibility is that the development of other performance-enhancing technologies such as stroke and swimming suits development directly following any drug testing interventions may also have obscured the influence of performance-enhancing drugs.

Swimming like other athletic events is highly competitive with exactly the same incentives to win races and consequently Olympic gold medals. Although performance -enhancing drugs cannot be directly quantified in freestyle swimming it is believed that they were being used to a similar extent as in other athletic events. As it is difficult to see any drugs effect in any improvement function model it is believed that the influence of performance-enhancing drugs in freestyle swimming is not as significant as the other athletic events examined so far.

8.10.d.(iii) Conclusion – Drugs intervention 1989

In conclusion the methods used to gauge the magnitude of any drugs effect could not find any significant influence. The step change factor in 1989 accounting for the widespread introduction of drugs testing in out of competition was small with large error bounds.

It is believed that freestyle swimming events are just as competitive as other athletic events, with similar incentives to win. The use of performance-enhancing drugs during the 1960, 1970s and 1980s is believed to have been as wipe spread in swimming as any other athletic event. It is therefore likely that freestyle swimming performances are not significantly influenced by any performance-enhancing drugs interventions. The performance in women's event may have peaked in the late 1970s and could be down to a drugs intervention effect; however the current models do not account for this and would require changes to the improvement functions.

Any influence from drugs interventions in freestyle swimming cannot be established within performance improvement trends in freestyle swimming. Therefore the step change factor accounting for the drug testing intervention in 1989 will be left out for the final calculation for the predicted limits of performance in each freestyle swimming event.

8.10.(e) Olympic influence

8.10.e.(i) Results – Olympic influence

The final intervention to be modelled for the freestyle swimming events is the Olympic effect, accounted for by a sine function with a period of 4 years. The magnitude of the sine function and the maximum effect of the Olympic Games from peak to trough is shown in Table 8.9 and represented graphically in Figure 8.25.

Table 8.9: The magnitude of the effect of the Olympics Games for each different swimming event

	Event	Intervention size (PII)	+/-	Intervention size (s)	+/-	Max effect (PII)	Max effect (s)
Men	100 m	0.76%	0.42%	0.22	0.12	2.35%	0.68
	200 m	0.69%	0.64%	0.44	0.41	2.68%	1.71
	400 m	0.53%	0.71%	0.74	0.99	2.49%	3.46
	1,500 m	0.90%	0.84%	5.10	4.74	3.49%	19.68
Women	100 m	0.93%	0.77%	0.31	0.25	3.41%	1.12
	400 m	0.86%	0.80%	1.35	1.26	3.33%	5.22

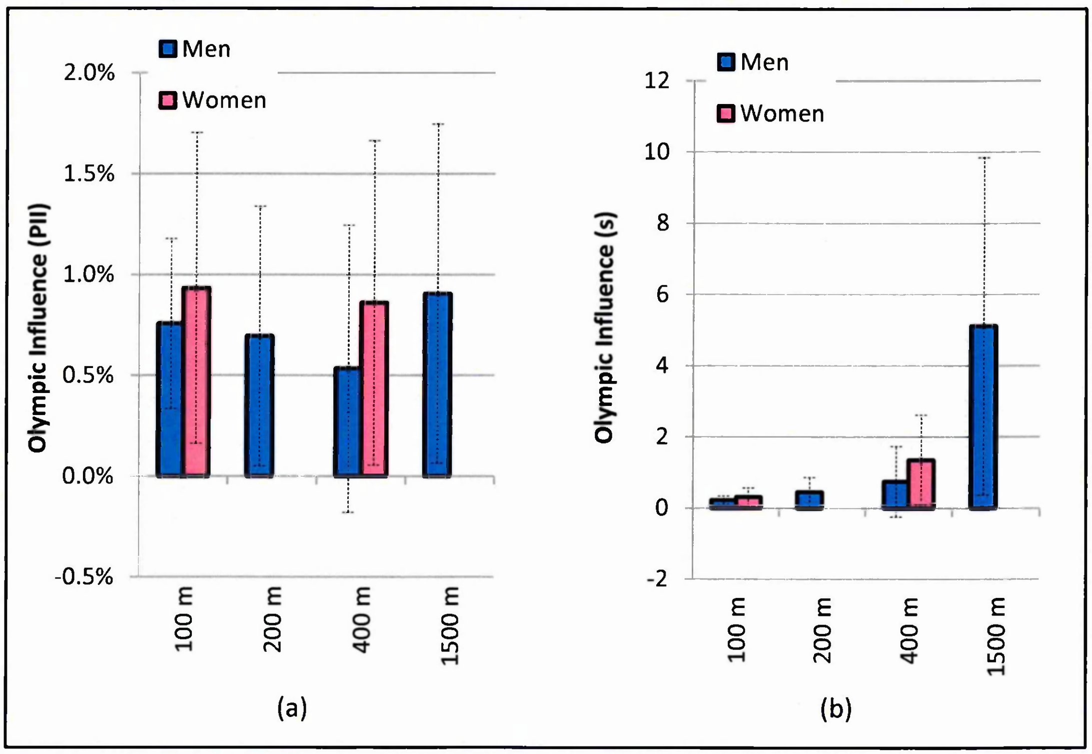


Figure 8.25: The magnitude of the effect of Olympics Games for each different freestyle swimming event shown in units of (a) percentage improvement in the performance improvement index and (b) increase in race time in seconds

8.10.e.(ii) Discussion – Olympic influence

The model to account for the Olympic Games effect on freestyle swimming was found to increase the goodness of fit for all available performance data. However the confidence intervals found on all Olympic parameters are very high, making it hard to confidently say that there is an Olympic effect in all events. The high error bounds are likely to be because of the reduced data set, but there are similar to the size error bounds found for the athletic field events.

Like with the other athletic events examined so far, the magnitude of the Olympic influence is again small. The Olympic amplitude term in freestyle swimming found to be between 0.53 (+/- 0.71) % in the men's 400 m to 0.93 (+/- 0.77) % in the women's 100 m. The maximum effect from peak to trough including error terms is very high, between 2.41% to 3.58% but this is mainly down to the high confidence intervals.

Across all events the size of the Olympic effect is similar and there are no significant differences between the different events, indicating that no single event experiences a greater Olympic effect than others. Finally as the Olympic influence is small, the sine wave function has very little or no influence on the quantification of other interventions.

8.10.e.(iii) Conclusion – Olympic influence

In conclusion there is a probable Olympic Games effect, which periodically influences freestyle swimming performance. This is demonstrated by the increase in goodness of fit of the improvement function with the addition of the Olympic sine wave function. The Olympic effect parameters are small with large confidence intervals making it hard to quantify the actual effect of the Olympic Games. This is similar to the Olympic influence found for the athletic events examined so far. As the Olympic effect is small this will not impact significantly on any other modelled interventions.

8.10.(f) Limits to athletic performance

8.10.f.(i) Results – Limits to athletic performance

The year when the global exponential function is within 0.1 % of the limit (essentially reaching the predicted limit) is shown below in Table 8.10 for all freestyle swimming events examined.

Table 8.10: The predicted natural performance limits for all freestyle swimming events examined shown with year at which the improvement functions are within 0.1% of this limit and shown with 95 % confidence bounds

	Event	L parameter (PII %)	+/-	L parameter (s)	+/-	Year when within 0.1 % of limit
Men	100 m	139.62%	4.77%	48.72	0.83	2017
	200 m	143.30%	6.42%	107.20	2.40	2010
	400 m	146.80%	6.44%	229.78	5.04	2006
	1,500 m	148.68%	4.83%	927.64	15.07	1996
Women	100 m	138.47%	4.43%	56.06	0.90	2006
	400 m	155.46%	6.45%	252.37	5.24	1993

Next the new limits of freestyle swimming performance are shown in Table 8.11. The interventions that are still believed to currently influencing swimming performance have also been accounted for, and performance limits adjusted accordingly. The only interventions which are believed to still influencing freestyle swimming performance are the 2000 swim suit full body suit introduction, the linear uptake of technology in the 1970s and finally the Olympic Games. The step changes accounting for drugs are believed not to exist and affect freestyle swimming performances.

Table 8.11: New predicted freestyle swimming performance limits taking into account interventions since 1948

		L parameter		Swim suit 2000		Linear uptake 1970-1976		Olympic Games		FAT		New limit with interventions	
Gender	Event	(PII %)	(s)	(PII %)	(s)	(PII %)	(s)	(PII %)	(s)	(PII %)	(s)	PII (%)	(s)
Men	100 m	139.62%	48.72	1.73%	-0.47	4.51%	-1.28	0.76%	-0.22	-1.45%	0.42	145.24%	47.17
	200 m	143.30%	107.20	2.70%	-1.38	2.39%	-1.52	0.69%	-0.44			150.26%	103.85
	400 m	146.80%	229.78	2.80%	-0.47	4.76%	-6.55	0.53%	-0.74			156.21%	222.02
	1500 m	148.68%	927.64	1.69%	-7.59	9.90%	-54.67	0.90%	-5.10			161.99%	860.29
Women	100 m	138.47%	56.06	3.04%	-1.00	11.54%	-3.70	0.93%	-0.31	-3.83%	1.276	149.69%	52.33
	400 m	155.46%	252.37	1.85%	-2.90	7.88%	-12.17	0.86%	-1.35			167.08%	235.95

8.10.f.(ii) Discussion – Limits to athletic performance

In the late 1990s the conventional fabric materials developed for swimming suits claimed to produce a lower drag than that of shaved skin and hence the development of full body suit in 1999/2000. The banning of non-fabric materials from 2010 onwards and the full covering nature of the swimming suits brought manufactures back to use similar fabric materials used in the original full fabric body suits. The "Jammer" style for men Knee to hip coverage and "Farmer John" for women', knee to shoulder are also now stipulated by the rules. It is believed that the fabrics developed for the first full body swimming suits was the dominant factor in the step change that occurred in 2000 and not the full body coverage. Therefore the 2000 step change has been left in, to account for drag reducing fabrics in the final limits calculations.

The global freestyle swimming performance development appears to be mainly influenced by the linear uptake of technology in the 1970s, but there is also a significant influencing effect from the swimming suit introduction in 2000.

The maximal levels of predicted performance improvement in all the freestyle swimming events examined are also similar at between 39.62 % and 55.48 %. The slightly higher values for the two women's events can be related back to the baseline performance figures, and that the women's events were slightly less competitive than the men's events at the baseline performance year. In addition to this the linear uptake of technology appears to have positively influenced the women's event to a greater extent. The magnitude of these original performance improvements are high in comparison to some running events and has been attributed to the less developed nature of the sport of swimming at the baseline year of 1948. The new maximum performance limits in the freestyle swimming events, taking into account interventions vary between 45.24 and 67.08 %. This shows a significant increase in performance which has been attributed to technological interventions.

Performance limits for the majority of events, seems to have already been reached, or be very close to being reached. The latest event to reach a predicted limit is the men's 100 m event in 2017. The improvements seen since the predicted limits were reached are down to external interventions such as the introduction of new swimming suits. This means that without extra interventions all freestyle swimming performance in 2017 may cease to improve and only vary season to season by the influence of the Olympic Games or World Championships.

8.10.f.(iii) Conclusion – Limits to athletic performance

The predicted magnitude of performance improvement for all freestyle swimming events from 1948 is similar and is attributed to swimming performance all being at a similar competitive level at the baseline year. Women are predicted to improve slightly more than men and this can be attributed to the women's being at a slightly lower competitive level in 1948 as well as the linear uptake of technology in the 1970s having a greater positive effect.

A greater absolute performance improvement is apparent in the freestyle swimming events when compared to running events. This is likely due to un-natural nature of swimming and that in 1948 it was at a lower level of competiveness and development than the sport of running. Since 1948 the optimisation of the strokes and other techniques has also plausibly led to a greater performance improvement in freestyle swimming. The linear uptake of technology in the 1970s currently influences swimming performance the most since 1948. The maximum influence of the 1970s technology uptake is greater in some events than that of the now banned polyurethane swim suits.

The modelled natural limits of swimming performance have already been reached in the majority of freestyle events, with the men's 100 and 200 m predicted to reach a limit very soon. If these limits are accurate in the future any advances in swimming performance will be from external interventions such as the introduction of new technologies. The findings here reflect the situation found in the other athletic events examined so far and could mean that very soon swimming and other athletic performance progression may stagnate.

8.11 Chapter summary

As swimming is believed to be a less innate athletic sport to humans it was envisaged that any technological influence will affect swimming performance more significantly than instinctive athletic events such as running. The only performance data set available for swimming was the top 3 performances in the freestyle swimming event, and therefore this was the only swimming event to be examined. It has been demonstrated that using the performance improvement index and a mean of the top 3 data set, there is no significant influence to the magnitudes of measured interventions or the trends in performance evolution. However the scatter in data is more apparent with a reduced data set which can be addressed in the future with an expanded data set.

The measured maximum levels of performance improvement seen in freestyle swimming appears to be greater than that seen in running and is attributed to the un-natural nature of swimming, lower competitive levels in 1948 compared to other athletic events and the continued optimisation of the freestyle swimming stroke. The interventions found to influence freestyle swimming performance have been summarised in Table 8.12. The 2008 and 2009 swimming suit step intervention are now not influencing performance figures as a rule change in 2010 banned the use of suit development in these years. Large error bounds are apparent for all parameters, which makes it hard to make firm conclusions and is likely down to the scatter arising from the smaller performance data set.

Table 8.12: A summary of the intervention seen in all freestyle swimming events

Event	Intervention gauged	Effect size (PII) %
100 m	Fully automatic timing	- 2.95% – -1.27%
All	Linear uptake of technology (goggles, hats and shaving down)	2.39% -11.54%
All	Fabrics developed to produce less drag than shaved skin - 2000 full body suits	1.69% – 3.04%
All	2008 – Polyurethane panels suit	0.95% – 3.57%
All	2009 – Full Polyurethane suits	2.03% – 5.18%
Selected events	Drugs	0.68% – 1.51%
All	Olympics	0.53% – 0.93%
All	Original performance limit	38.47% – 55.46%
All	New performance improvement limit	45.24% – 67.08%

Chapter 9: Speed Skating: Long course

9.1 Introduction

Within this study, speed skating is the last athletic event to be examined for the influence of interventions upon athletic performance. Speed skating is a very modern athletic race event with competitions only commencing in the 18th century. Similar to swimming, speed skating is not a natural human locomotion and skating techniques are not intrinsic to humans. In addition to this ice tracks or rinks where speed skating could take place were rare in the early stages of speed skating and only existed in countries where climatic conditions allowed for ice in the winter. This meant initially there was a smaller competing population in comparison to other athletic events. The invention of artificial ice and indoor ice rinks allowed for all year round competition as well as speed skating to be participated in countries without ideal outdoor ice conditions. This expanded the competing population and accelerated the evolution of speed skating performances. With speed skating being such a young sport in comparison to other athletic events at the baseline year in 1948, greater performance improvements are likely to be observed. Interventions which improve speed skating performance are believed to be primarily the introduction of clap skates, adoption of full body skin suits and the development of artificial and indoor ice rinks. The aim of this chapter is to identify and quantify the interventions and technologies that have significantly influenced speed skating performance from the baseline year of 1948. The aim of this chapter can be broken down into the following objectives:

The objectives of this chapter are as follows:

1. To explore intervention history in the athletic sport of speed skating
2. To gauge the performance improvements in the sport of speed skating
3. To identify the interventions that are believed to be present
4. To apply intervention modelling techniques to speed skating performance data
5. To explore the magnitudes and types of interventions seen in long course speed skating events and make comparisons to the other athletic events examined so far.

9.2 Long course speed skating

Athletic racing events held on a surface of ice using footwear called ice skates is commonly called competitive speed skating. Evidence of humans traversing ice using skate technology dates back to 3000 b.c. with a the oldest known skates found in

Switzerland (Formenti & Minetti 2007). Early skates were made from the leg bones of large animals with holes bored out to allow the fitting of leather fixing straps. Originally skates were used a means of convenient transportation on ice surfaces in winter periods. There is no evidence found of ancient ice skating competition and it is believed that it was not until the 17th century where speed skating events originated. The first official speed skating club was formed in Edinburgh in 1642 and the first official speed skating event was held in England on the Fens in 1763. The spread of speed skating was instigated by the invention of the first all iron skates in Scotland in the 16th century (Speed skating Canada 2012).

9.2.(a) History of competitive speed skating

There is no evidence that speed skating races took place in the ancient world, and it is believed the first ever speed skating race took place in England only about 250 years ago in 1763. The frozen Fen Rivers of East England were used to stage a 24 km race (Speed skating Canada 2012). The first speed skating event to be held that resembled todays modern long course skating competition was held in Oslo, Norway in 1863 (International skating union 2012). Following this competition the first World speed skating championships were held in Amsterdam in Holland in 1889 and consisted of four men only events: the 500, 1500, 5000 and 10000 m. As a result of the global growth of speed skating an international governing body was step up to administer the sport, this was called the International Skating Union (ISU) and was formed in 1892. Speed skating was part of the first Winter Olympic Games in 1924 and consisted of the same four events that were held in the first World Championships. In addition a combined medal was given to the best speed skater to complete all four events and was called the “men’s all-round event”. This was the first and only time Olympic medals were given to competitors in this way for competing in multiple speed skating events. Women started competing at the Olympic Games in speed skating events in 1960, with a 1000 and 3000 m event along with the 1500 and 5000 m events which already existed for men. In the 1976 Winter Olympics the men also competed in the 1,000 m event. Women were also given the 5000 m event in the 1984 Olympics. In 1994 the Winter Olympics were held out of synchronisation with the summer Olympics, but held every four years. The last Olympic event to be introduced was the men’s and women’s team pursuit at the 2006 Olympic Games. The Speed skating world championships consisted of all the same events as described for the Winter Olympics.

‘Long track’ speed skating describes the type of track that events are held on. Originally all speed skating events were held on 400 m long tracks similar in length to a standard athletics track. These tracks were later designated long course tracks after the introduction of shorter speed skating competition in the early 20th century. Currently there are two distinct types of speed skating event, long track speed skating and short course speed skating, the difference between the competitions being the track specifications. Short track speed skating events only started at the beginning of the 20th century, were not part of the winter Olympics in a recognisable format until 1992 and short track World championships were only held from 1976 onwards. The later development of short track speed skating means that there is more performance data available for long track speed skating, this event type was selected to be examined within study, and short track events were omitted.

Table 9.1: Long course speed skating events participated at the Winter Olympic Games

Event	48	52	56	60	64	68	72	76	80	84	88	92	94	98	02	06	10
Men's 500 m	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Men's 1000 m								•	•	•	•	•	•	•	•	•	•
Men's 1,500 m	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Men's 5,000 m	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Men's 10000 m	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Men's team pursuit																•	•
Women's 500 m				•	•	•	•	•	•	•	•	•	•	•	•	•	•
Women's 1,000 m				•	•	•	•	•	•	•	•	•	•	•	•	•	•
Women's 1,500 m				•	•	•	•	•	•	•	•	•	•	•	•	•	•
Women's 3,000 m				•	•	•	•	•	•	•	•	•	•	•	•	•	•
Women's 5,000 m											•	•	•	•	•	•	•
Women's team pursuit																•	•

9.2.(b) Long course speed skating

The dimensions of a typical long course speed skating track are depicted in Figure 9.1. The various starting positions of the different race events are also shown in this figure. On the back straight there is a change over point where the skaters on the inside and outside lanes cross over each other's path and change lanes. In typical long course speed skating events only 2 skaters compete at the same time, with various heats to decide who competes in the final (World of Sports Science 2012).

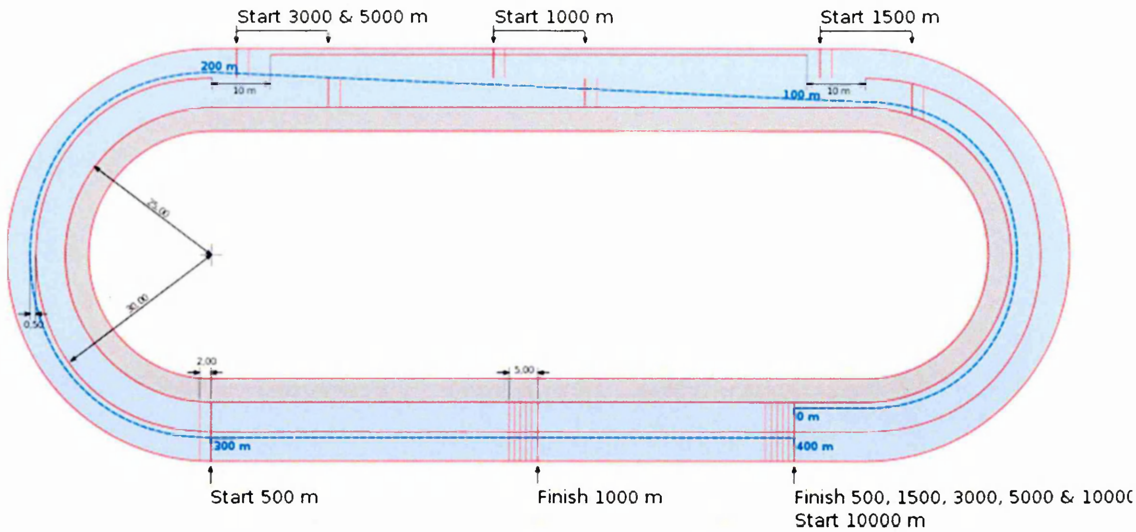


Figure 9.1: The dimensions of a long course speed skating track with two lanes (McSmit 2009)

The 500 m is the shortest long track speed skating event, and lasts around 35 seconds, with the current world record standing at 34.03 seconds which was set at the 2007 Winter Olympic Games by Jeremy Wotherspoon of Canada. In Long track speed skating events only 2 skates compete at the same time. The 1,000 m is the next longest distance event and was originally introduced for the women only at the Olympic Games. The current world record in the men's 1,000 m is 1 minute and 6.42 seconds set by Shani Davis in 2009 with an average completion speed of 15.06 ms^{-1}. This makes this event on average faster than the shorter 500 m event. The 500 and 1000 m are considered sprinting events where an explosive start with high acceleration followed by a high average speed throughout the race is required. The next speed skating event distance is the 1,500 m and current world record for the men is 1 minute and 41.04 seconds with an average speed of 14.85 ms^{-1}. The 1,500 m event and above are considered distance events where a steady pace and maintaining skating form dictates success. The final three individual long course speed skating event distances examined in this study are the 3,000, 5,000 and 10,000 m, with current men's world records at 3 minutes 37.28 seconds, 6 minutes 3.32 seconds and 12 minutes 41.69 seconds respectively. The average race speeds in 2010 for the men's and women's speed skating events examined are shown in Figure 9.2.

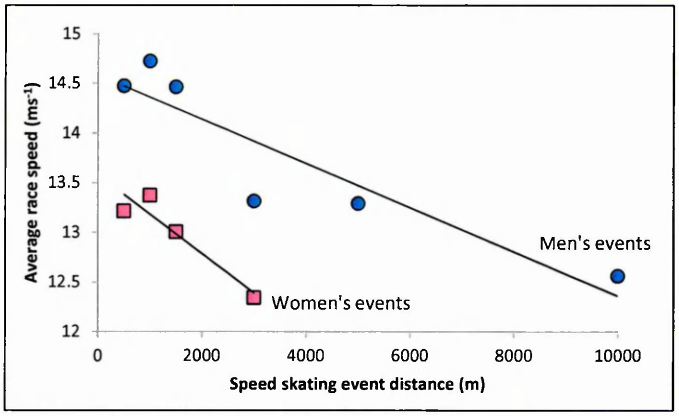


Figure 9.2: Average race speed in 2010 for the various long course speed skating events examined, shown with simple linear trends fitted in excel

The current attire for a long course speed skater is a tight fitting skin suit with a hood, covering the entire body as depicted in Figure 9.3. The skin suit's aim is to minimise drag caused by air resistance. Glasses are also worn by some skaters to protect their eyes from the wind resulting from the consistent high speeds. Unlike the short course speed skating events the skaters are not required to wear helmets as crashes are less common. Competitive long course speed skating attire was not always like this and the development of speed skating clothing will be examined in a later section.

Figure 9.3: Various long course speed skating events (Canada.com 2009 & Speed Skate World 2009)

9.2.(c) Result statistics available:

Speed skating result statistics are surprisingly more complete than swimming events, and data for the top 25 list for men and women in many events goes back to before 1948. The reason for this is more than likely down to the early formation of the ISU and the standardisation of metric long course speed skating events. The available performance data in long course speed skating events for men and women is shown previously in table 4.3. From 1948 top 25 performance lists for men are available for all individual events distances: 500, 1000, 1.500, 3.000, 5.000 and 10.000 m. For the women the 500, 1.000, 1.500 and 3.000 events are the only events with top 25 performance data available. As speed skating championship seasons are held over the winter period results of a season straddle over two years, i.e. 1947/1948. The top performances usually come towards the end of the season and overlaps into the new year. For simplicity the 1947/1948 season will be designated by the year 1948 and all top times for that season will be all counted.

9.3 Historic interventions in speed skating events

The major interventions which are believed to influence long course speed skating performance are shown the time line depicted in Figure 8.2.

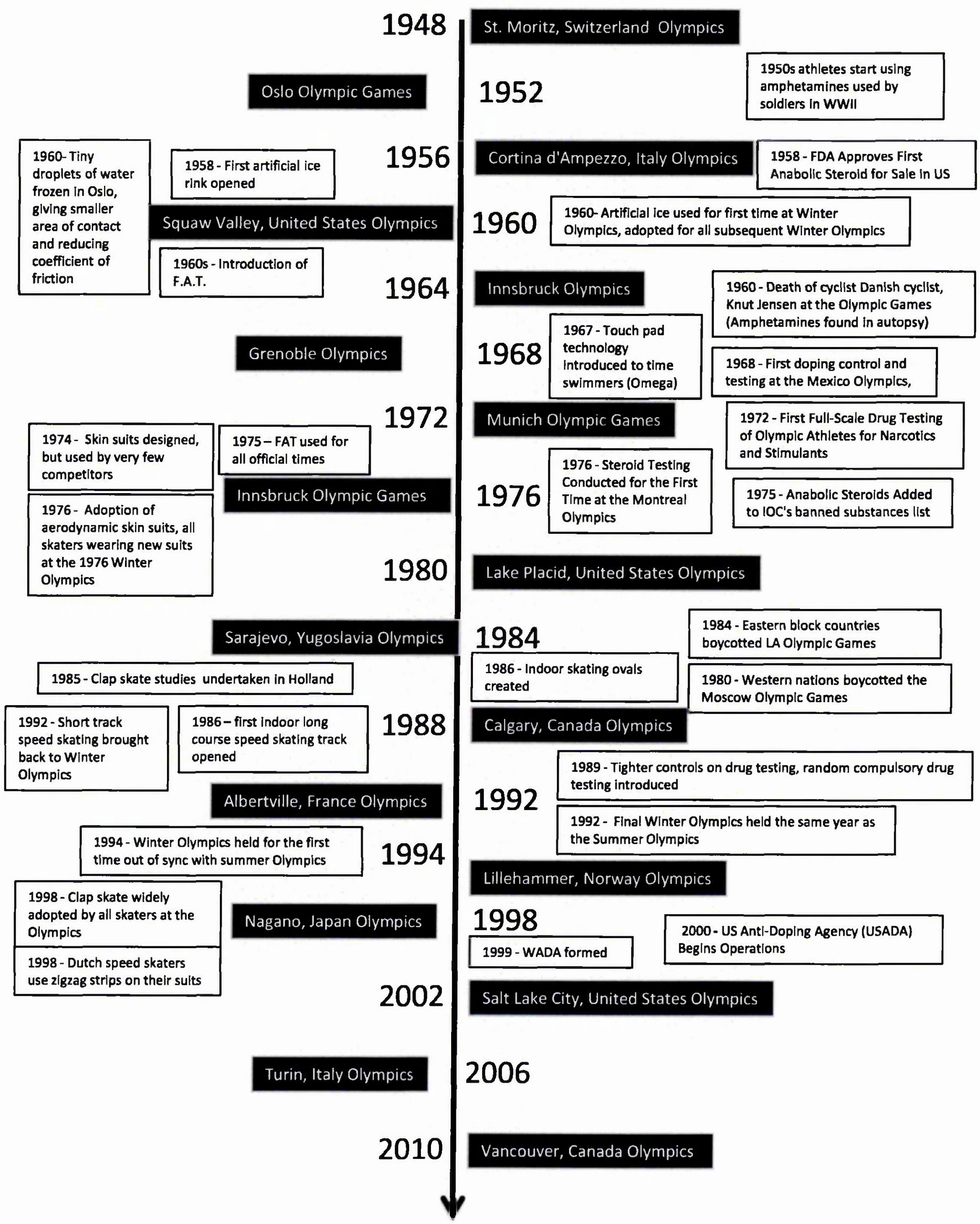


Figure 9.4: Time line of interventions from 1948 for long course speed skating events

9.3.(a) Ice development

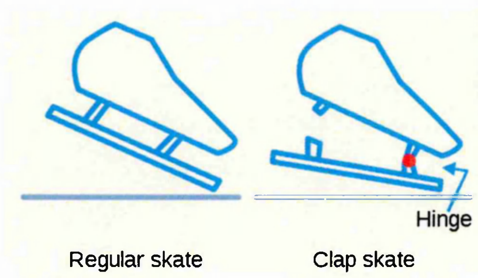
The development of the ice surface is an often overlooked factor in the evolution of speed skating performances. A smooth and low friction ice surface is essential in setting elite speed skating performance times in modern competitions. However a smooth consistent ice surface is only a modern invention, with the formation of artificial ice rinks. Artificial ice rinks were first devised in Victorian London in 1841 (History House 2012), but as the technology was in the early stages of development, artificial ice rinks were rare. It was not until the 1950s and 1960s that artificial outdoor ice rinks started to become the norm and in 1986 that the first indoor long course speed skating was opened in Heerenveen, Holland. An ice resurfacing machine which smoothed the ice was also introduced in 1949 and is commonly called a "Zamboni" after the inventor. Now all international speed skating competitions are held on indoor ice rinks, with low friction smooth surface. From 1960 onwards the ice in the Bislett stadium in Oslo was prepared by spaying ting droplets of water which were frozen in place. This resulted in a smaller area of contact with the skate blade and reduced the coefficient of friction between the blade and the ice (Kuper & Sterken 2003). The new ice preparation technique developed in Oslo is believed to have been taken up by other ice rinks throughout the 1960s. The reduction in friction between the skate blade and the ice is believed to have increased skating speed and increased speed skating performance in this period.

9.3.(b) Fully automatic timing

As with the athletic track events all official performance times in long course speed skating events were recorded using fully automatic timing systems from 1975 onwards. As with the running events, the introduction of fully automatic timing will increase the accuracy of timing measurement and alleviate human reaction time error. The shortest long course speed skating event, the 500 m lasts approximately 35 seconds. It has been previously found that when examining for a fully automatic timing effect in events of around this length that the magnitude of the effect is hard to gauge. Therefore for all speed skating events no fully automatic effect is intended to be gauged.

9.3.(c) Development of ice skates – Clap skates

Ice skates are the dominate piece of technology and dictates the nature of speed skating events. Original skates were made from leg bones of animals like horses and cows, but were not used for skating competitions. Wooded skates were the next to be developed around the 10^{th} to the 16^{th} century (Speed skating Canada 2012). Early wooden skates were probably completely made from wood but were later designed incorporated a metal running surface. In 1592 all iron skates were developed in Scotland and were the believed to be the first skates used in competition (International skating union 2012). The next development in skate technology came in the 19th century with the development of all steel skates. The steel materials allowed designers to make the blade thinner and stronger than the previous all iron blades. The thinner blades inevitably led to less friction between the blade and ice and allowed skates to travel faster. Steel skates were combined with a boot in 1885 to create an all in one skate, which is recognised today as a standard ice skate. Before this point the term skates only referred to the blade section which was tied to the foot of a skater. The final major development in speed skates design came a century later in the 1980s, where a hinged joint was placed in the toe section of the skate. The hinge allowed for greater biomechanical efficiency of the skating action as the blade could be kept in contact with the ice for a greater length of time (Schenau et al. 1996, de Koning et al. 2000, Kuper & Sterken 2003,). The increased efficiency of the skate allowed for faster speeds to be attained and thus increased speed skating performance. This type of skate was called a Clap skate due to the sound they made when the boot came in contact with the metal blade. In the 1980s the clapped skates were only adopted by a few non elite speed skates. Clap skates were not extensively adopted by the elite field as it was believed they did not enhance skating performance. The Dutch women's team adopted the clap skate in the 1996/1997 season with great success (Chang 1998). This led to the true global adoption of clap skating technology before the 1998 Nagano Winter Olympic Games and a surge of World records being set during this season.



(a)

(b)

Figure 9.5: (a) Schematic of a clap skate (b) Clap skate in use in competition (McSmit 2008, Mysid 2005)

9.3.(d) Skin suit

On the outside ice rinks speed skaters were originally more concerned with keeping warm, than cutting through the air with the least friction. Original speed skaters attire consisted of thick baggy clothes with a woollen hat. The first speed skating world Champion Jaap Eden and his attire is shown in Figure 9.6.

Figure 9.6: Japp Eden, first official Speed skating world champion (Robbot 2005)

A tight fitting speed skating suit was first introduced in1974 by an ex-Swiss speed skater Franz Krienbühl (Kuper & Sterken 2003). Initially these suits were used by very few speed skaters and were not taken seriously. However at the 1976 Winter Olympic Games all speed skating competitors were using a tight fitting speed skating suit. The suits were an evolution in speed skating attire and were believed to reduce aerodynamic drag. With the high speeds experience in speed skating, the reduction in coefficient of drag and projected front area that came from these suits is therefore likely to have had a large influence on performances. Unlike running speed skating full covering skin suits, speed skating suits have been adopted by all competitors and would are unlikely to be used if they do not give an advantage. Skins suits are not as effective in running as running events are carried out lower speeds. In swimming, full body suits which reduce the coefficient of drag and frontal area are more effective than in running as water is approximately 784 times denser than air at sea level. Another development of speed skating skin suits came in 1998 where zigzags profiles were places on to the arms of the Dutch speed skater's suits (Kuper & Sterken 2008). The zigzag profile is believed to reduce pressure drag by reducing the aerodynamic wake. Current speed skating skin suits are depicted in Figure 9.3.

9.4 Results – Speed skating performance improvement

The evolution of performance in the men's and women's long course speed skating events has been shown as raw performance time in seconds against historic year in Figure 8.4.

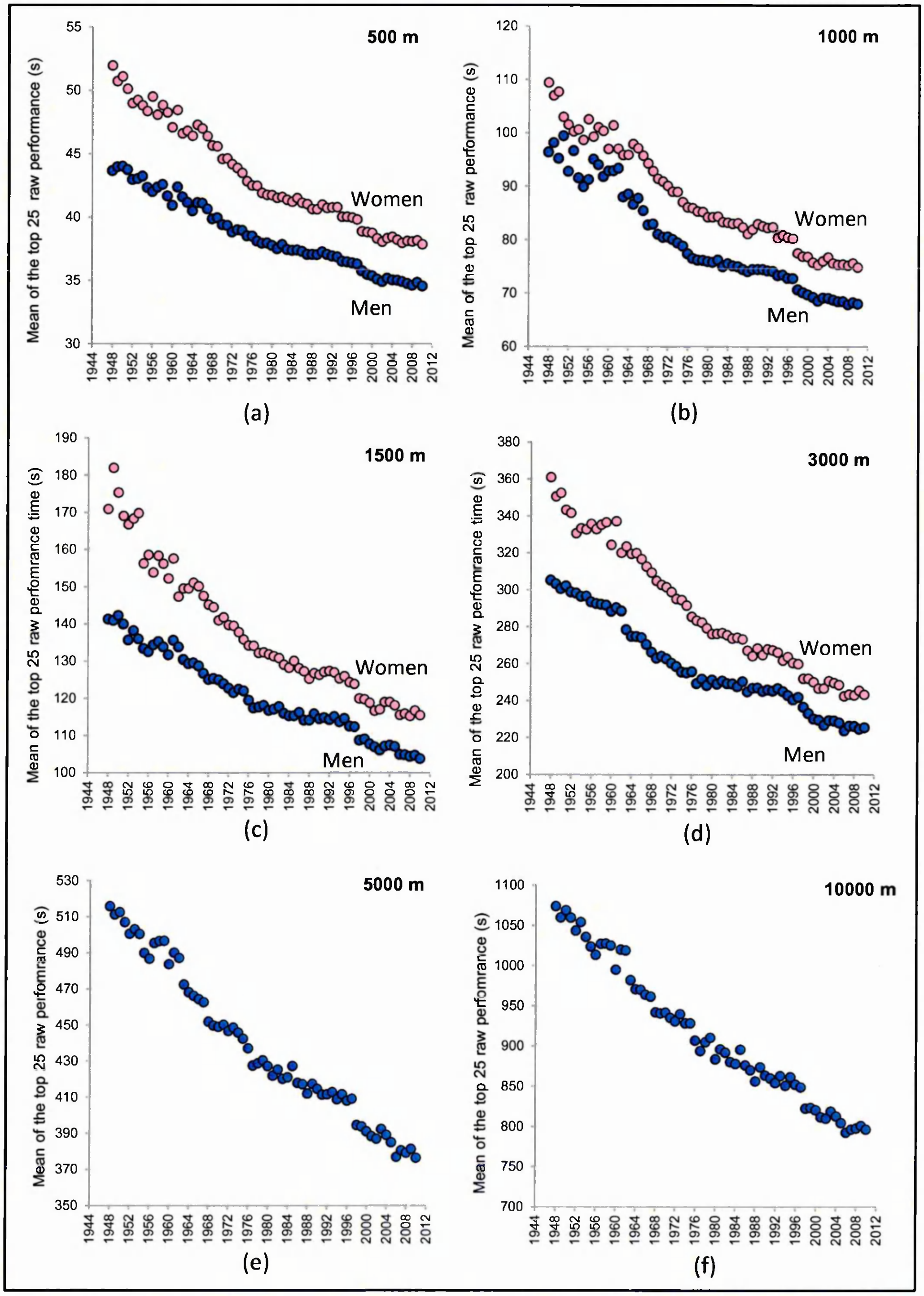


Figure 9.7: Mean of the top 25 raw long course speed skating performance data from 1948 in the men's and women's long course speed skating events with a distance of (a) 500 m, (b) 1000 m, (c) 1500 m (d) 3000 m and for men only (e) 5000 m and (f) 10000 m.

The raw performance times have been converted into average speed in completing the different distance events and are shown for each year from 1948 in Figure 8.5.

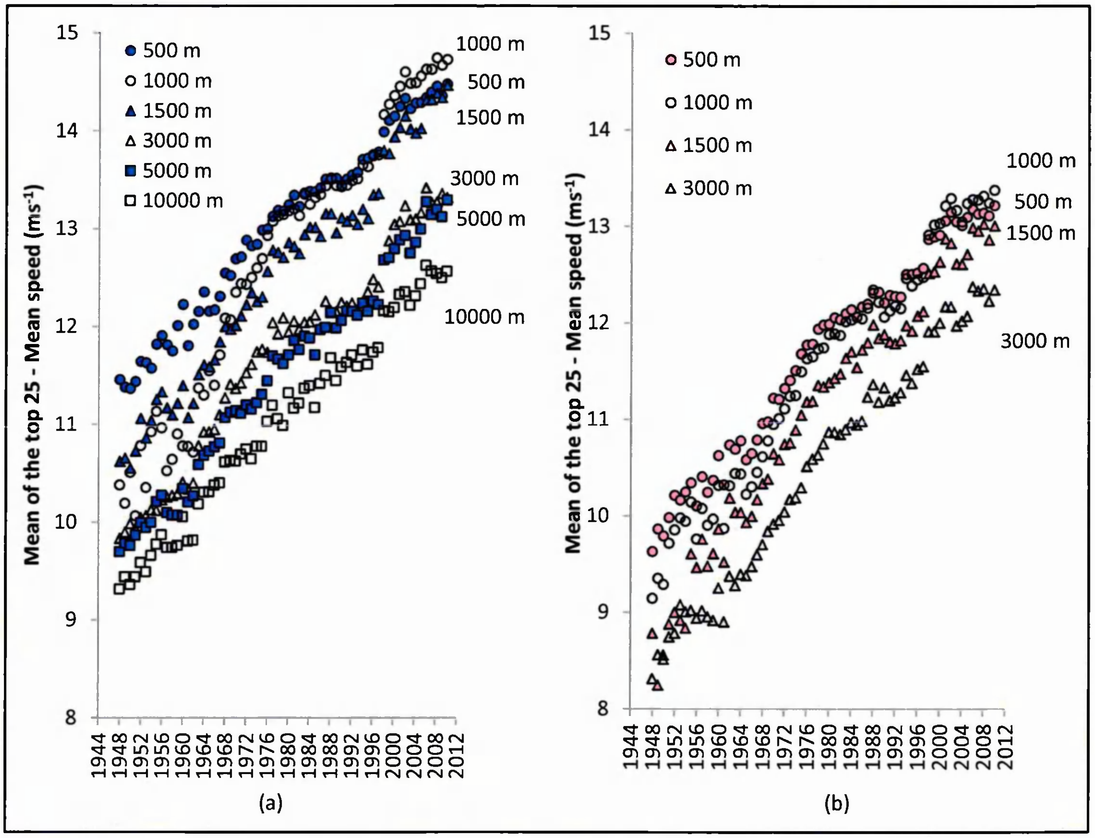


Figure 9.8: Mean of the top 25 long course speed skating performance data converted into the average speed to complete the race for each year from 1948 in events for (a) men, and (b) women.

The raw performance figures have now been converted into a performance improvement index values, each year from 1948 and are shown in Figure 8.6.

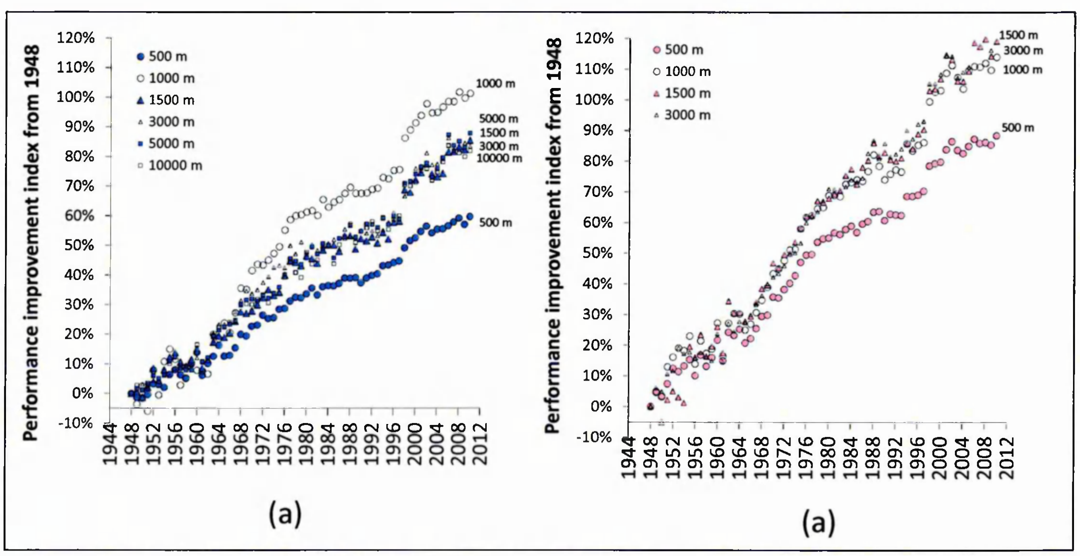


Figure 9.9: Mean of the top 25 long course speed skating performance data converted into a performance improvement index from 1948 in events for (a) men, and (b) women.

For each long course speed skating event examined the maximum magnitude in terms of percentage increase in the performance improvement index, and the year at which this maximum value was found, has been represented graphically in Figure 6.10.

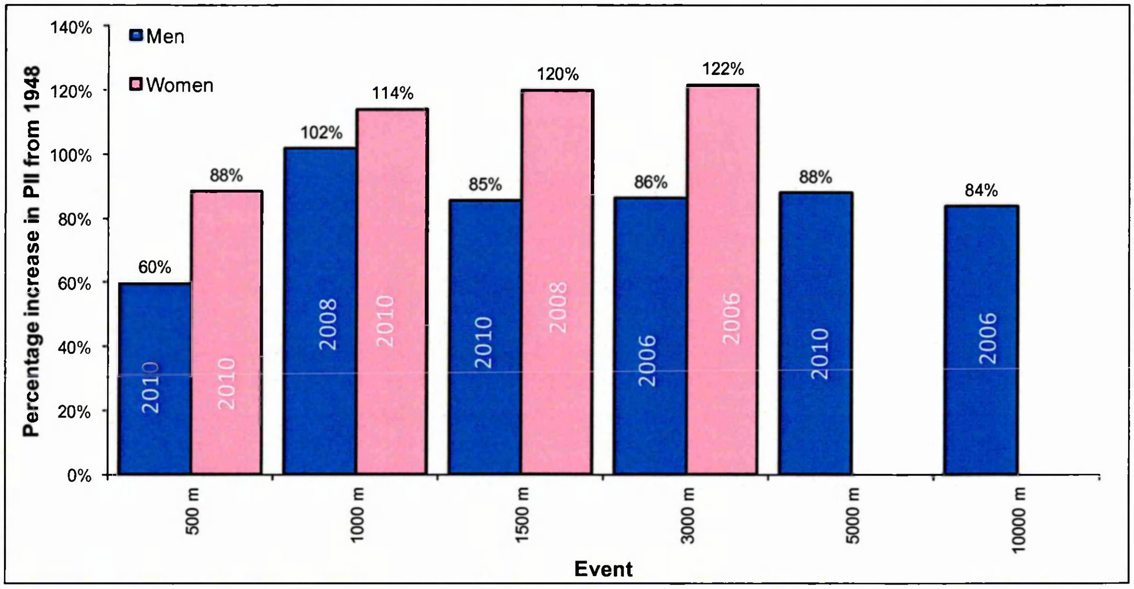


Figure 9.10: Maximum percentage increase in the performance improvement index from 1948 for all long course speed skating events, shown with year of peak performance.

9.5 Discussion – Speed skating performance improvement

9.5.(a) General trend in performance improvement

The general improvement trend (Figure 9.8) seen in long course speed skating development for men and women are similar to the trends observed in the other athletic events examined in this study. This trend is exponential in nature which has been hypothesised to be primarily driven by an increase in competition population and to a lesser extent the better understanding training techniques and nutrition. A unique feature of the performance improvement trend in speed skating events appears to be that the rate of increase in performance is greater, and this result in a higher predicted maximum performance improvement. The steeper gradient means that speed skating has improved faster from 1948 when compared to the other athletic events examined.

The faster development of speed skating performance may be down to several reasons. Firstly similarly with swimming, speed skating not a natural human movement, skating technique is likely to have not been optimised in 1948, and so continued to be developed over the period where performance data has been examined. This may have resulted in speed skating performances increasing at a faster rate. Secondary the size of the competing population of speed skating may have increased at a greater rate when compared to other athletic events. This is because initial speed skating competitions could only be accessed by a small percentage of the world's population, as suitable ice courses were confined to countries with a suitably cold climate. With the development of artificial ice and indoor ice rinks, arenas suitable for speed skating events have spread throughout the world and thus increased the size of the competing population. The continued development of speed skating performances may be as a result of a continued increase in the size of the competing population, as more and more of the world's population have access to speed skating arenas, as more are built. Finally the interventions such as the clap skate in 1998 and skin suits in the mid-1970s may have had a large influence in driving the increases in performance through a witnessed uptake period.

9.5.(b) Maximal performance improvement

Examining Figure 6.10 the maximum improvement observed in all speed skating events, is similar, with the men's events improvement between 60 % to 102 % in the 500 and 1000 m respectively. For women the maximum performance improvement is between 88 % and 122 % in the 500 and 3000 m respectively. The similar levels of improvement within sex specific events may be down to base line performance level in 1948 being similar across all events. Women generally see a greater maximum performance improvement and this has been attributed to the women's speed skating events being less developed in 1948 when compared to men's events. In line with this, the overall percentage improvement in speed skating is generally the greatest for all the athletic events examined. This is believed to be due to the greatly reduced size of the competing population for speed skating in 1948, which would have made the baseline performance measure lower compared to other athletic events. All maximum performance improvement from 1948 are all in the most recent decade and this indicates further still that speed skating performance are still developing and is driven by an increasing competing population along with recent technological developments such as the clap skate.

9.5.(c) Interventions

There appears to be an increase in the rate of performance improvement in all speed skating events in the mid-1960s this has been attributed to the continued development of artificial ice. Again in mid-1970s there also appears to another increase in in the rate of change performance and this has been attributed to the adoption of skin suits in 1976. The late 1990s also saw increase in the rate of change of performance and this has been attributed to the adoption of clap skates around 1998 as well as the continued development of skin suits such as the adoption of zigzag profiled suits in

1998. There is no observable drop in speed skating performances around the mid-1970s with the introduction of fully automatic timing.

9.6 Intervention that will be modelled: Predicted interventions

Drugs will be modelled using the same methods developed during the examination of other athletic events. However it appears that in 2000 there in no noticeable drop in performances and this step change due to better drug testing technologies will not be modelled. The adoption of clap skates in this period is likely to have masked the effect of this drugs intervention. In addition to this fully automatic timing will not be modelled as no visual effect can be seen. All long course speed skating events are also not of a sufficient duration making the effect of fully automatic timing hard to be accurately gauged. The introduction of indoor long course ice rinks appears to show no significant increase in performance around 1986/1987 and therefore will also not be modelled.

From 1960 onwards there appears to be an increase in the rate of change over the global improvement trend this has been attributed to improvement in the formation of artificial ice and a reduction in friction. The artificial ice intervention will be model first though a step change in 1963 and then with a linear uptake from 1960 – 1968. For each different speed skating event the best fitting model will be used in the final improvement function. The same method will be used to account for the uptake and use of clap skates. A step change in 1998 will be first used to model the full adoption of clap skates and then a linear uptake of clap skates from 1996 – 2002 will be employed. The best fitting model will be used in the final improvement function. A step change in 1976 will be used to account for the full uptake of skin suits which have been shown to reduce drag. No effect can be modelled in 1998 for the effect of zigzag profiles on skin suits as this is at the same time of clap skate uptake. The Winter Olympics were held out of phase from the summer Olympic Games in 1994. To account for this a new Olympic sine function with a different phase shift will be applied to performance data post 1994.

9.7 Improvement function generation steps

The intervention modelling steps used to optimise the improvement function for all speed skating events has been summarised in Table 7.4.

Table 9.2: Improvement function generation steps for the men's and women's long course speed skating events

Step no.	Intervention modelled:	Model description:	IF GUI model no.
1	Global improvement	Global improvement trend	2
2	Clapped skate step change 1998	Step change 1998	3
3	Clapped skate linear uptake	Linear uptake 1996 - 2002	41
4	Artificial ice step change	Linear uptake (1996 - 2002) and step change (1963)	74
5	Artificial ice linear adoption	Linear uptake (1996 - 2002) and Linear uptake (1960 - 1968)	75
6	Skin suit introduction 1976	Step change 1976	76
7	Drug testing step change 1989	Step change 1989	77
8	Drugs linear uptake	Drugs uptake 1968-1988	78
9	Drugs linear uptake and decline (best start date)	Drugs up and decline xxxx –1988 – 1994	81
10	Drugs linear uptake and decline and Olympics with Olympic start year	Periodic function of four years from 1948	83/84

For each fitting step the change in goodness of fit values (adjusted regression coefficient) has been plotted for each fitting step of improvement function to men's and women's long course speed skating events in Figure 9.11 and Figure 9.12 respectively.

9.8 Results – graphical representation and goodness of fit

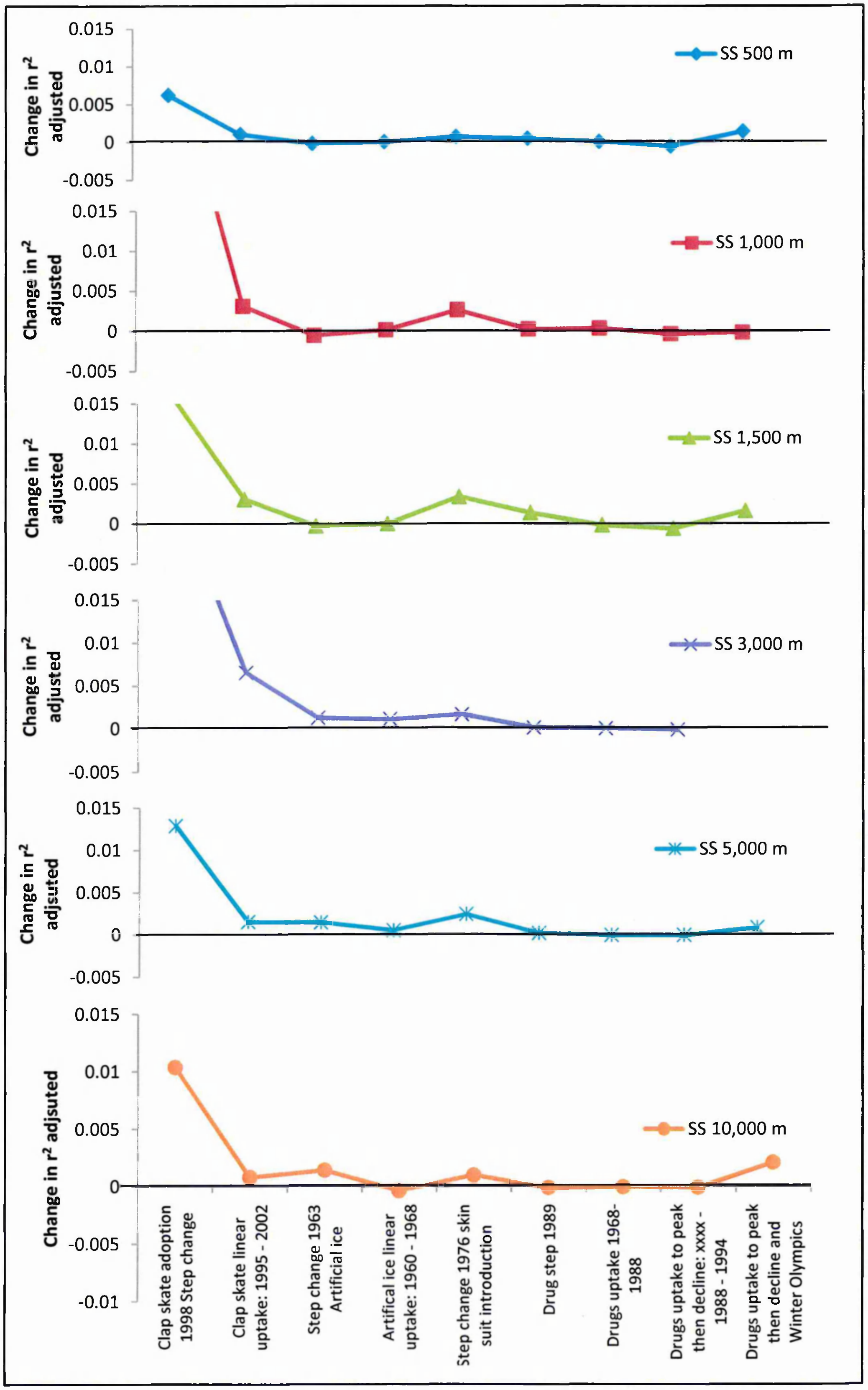


Figure 9.11: Change in adjusted regression coefficient for the modelling steps men's long course speed skating events examined

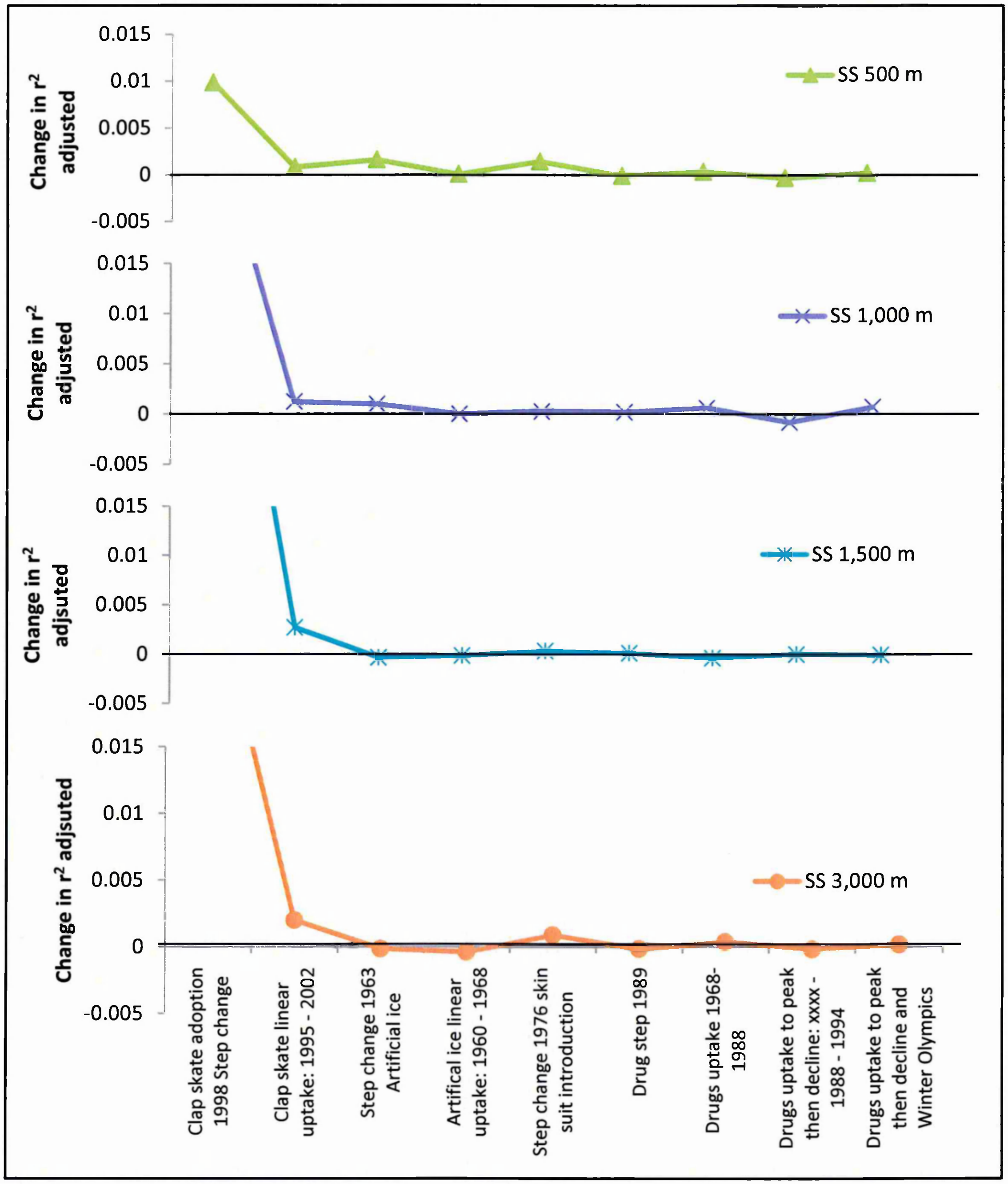


Figure 9.12: Change in adjusted regression coefficient for the modelling steps women's long course speed skating events examined

Any unexpected parameter values found during the fitting procedure for all speed skating events have been noted and displayed in Table 9.3. It appears that no drug effects could be found in the women's 1,500 m in 1989 and a skin suit effect could not be modelled in the men's 10,000 m event.

Table 9.3: Interventions for the different events that have been excluded from the final improvement function model as unexpected parameters were found

Event	Modelling step/ intervention	Reason for omitting from final model
Men's 10,000 m	Skin suits step change 1976	Negative effect found
Women's 1,500 m	Drug step change 1989	Positive effect found
Women's 500 & 1,000 m	Artificial ice: step change and linear uptake	Negative effect found

Taking into account which improvement function fitting steps showed an improvement in fit as well as the unexpected parameters found, the final improvement models tailored for each speed skating event are shown below in Table 9.4.

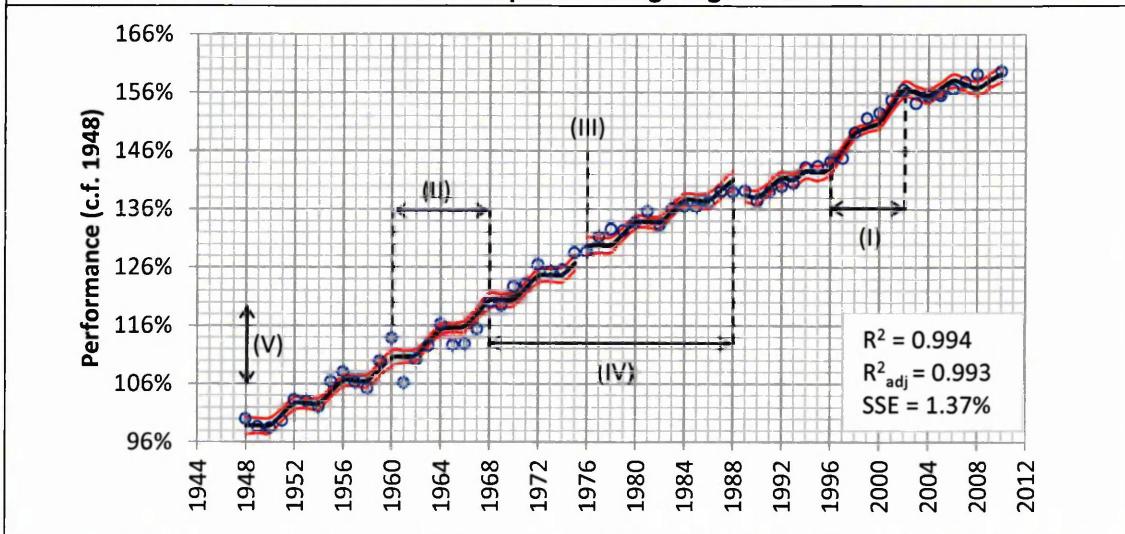
Table 9.4: Final improvement function model and GUI assigned model number, customised for each event

Event	Model description	Model type
Men's 500 m	Expo + linear clap skate (1996-2002) + linear artificial ice (1960-1968) + step change suits (1976) + drugs uptake (1968-1988) + Winter Olympics	Expo + 2 linear + 1 int + drugs + Winter Olympics
Men's 1,000 m and 3,000 m	Expo + linear clap skate (1996-2002) + linear artificial ice (1960-1968) + step change suits (1976) + drugs uptake (1968-1988)	Exp + 2 linear + 1 int + drugs
Men's 1,500 m and 5,000 m	Expo + linear clap skate (1996-2002) + linear artificial ice (1960-1968) + step change suits (1976) + drugs step (1989) + Winter Olympics	Expo + 2 linear + 2 ints + Winter Olympics
Men's 10,000 m	Expo + linear clap skate (1996-2002) + artificial ice step change (1963) + step change suit (1976) + Winter Olympics	Expo + 1 linear + 2 ints + Winter Olympics (start year)
Women's 500 m and 1,000 m	Expo + linear clap skate (1996-2002) + step change suits (1976) + drugs uptake (1968-1988) + Winter Olympics (Start year)	Expo + 1 linear + drugs + Winter Olympics (start year)
Women's 1,500 m	Expo + linear clap skate (1996-2002) + step change suits (1976) + Winter Olympics (Start year)	Expo + 1 linear + 1 int + Winter Olympics (start year)
Women's 3,000 m	Expo + linear clap skate (1996-2002) + step change suits (1976) + (drugs uptake 1968-1988) + Winter Olympics (Start year)	Expo + 1 linear + 1 ints + drugs+ Winter Olympics (start year)

9.9 Final improvement models – long course speed skating events

The final improvement functions models for all the long course speed skating events examined have been represented graphically from Figure 9.13 to Figure 9.22. Each intervention accounted for within the final improvement function has also been labelled and the size of the different parameters summarised.

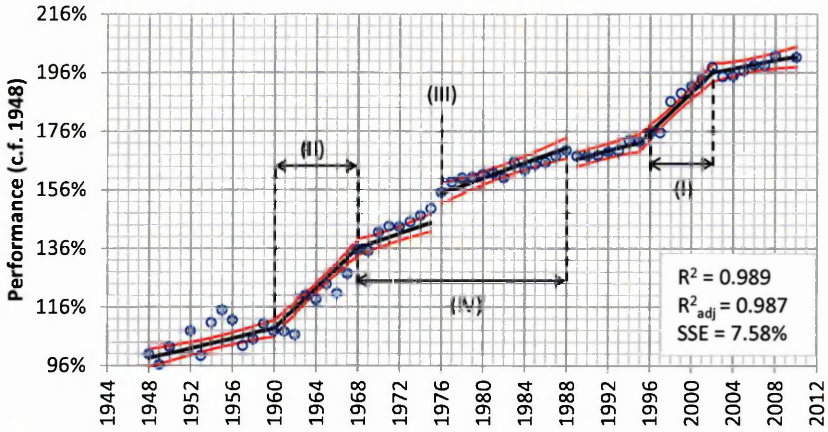
Men's 500 m speed skating long course



	Intervention	Parameters
	Global improvement	L=147.72% (± 7.30); a=0.013292 (± 0.01329); b=14.5142 (± 6.99)
I	Clap skate	$LU1=1.42\%yr^{-1}$ (± 0.42); $LU1_{peak}$=9.94% (± 2.97); $LU1_{start}$=1996 ; $LU1_{end}$=2002
II	Artificial ice	$LU2=0.25\%yr^{-1}$ (± 0.40); $LU2_{peak}$=2.01% (± 3.17); $LU2_{start}$=1960 ; $LU2_{e1nd}$=1968
III	Skin suit	k_1=100.78% (± 1.97); k_1year=1976
IV	Uptake of drugs before stricter drug testing	$D=0.12\%yr^{-1}$ (± 0.11); D_{peak}=2.42% (± 2.12); D_{start}=1968 ; D_{end}=1988
V	Winter Olympic Games	Amp A=0.94% (± 0.56)
		R^2=0.994; R^2_{adj}=0.993; MSE =0.03%; SSE=1.37%

Figure 9.13: Final improvement function model for the men's 500 m speed skating event

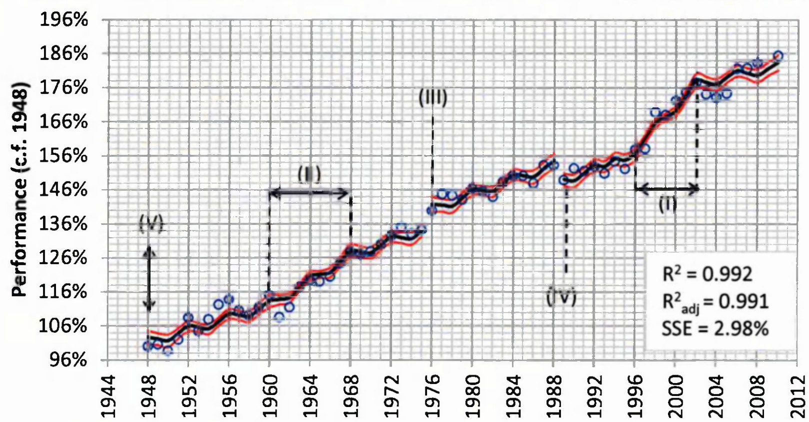
Men's 1,000 m speed skating long course



	Intervention	Parameters
	Global improvement	L=162.29% (± 2.18); a=0.007796 (± 0.01251); b=15.5292 (± 13.61);
I	Clap skate	$LU1=2.36\%yr^{-1}$ (± 1.01); $LU1_{peak}$=16.54% (± 7.04); $LU1_{start}$=1996 ; $LU1_{end}$=2002
II	Artificial ice	$LU2=2.46\%yr^{-1}$ (± 0.85); $LU2_{peak}$=19.72% (± 6.80); $LU2_{start}$=1960 ; $LU2_{e1nd}$=1968
III	Skin suit	k_1=105.96% (± 4.15); k_1year=1976
IV	Uptake of drugs before stricter drug testing	$D=0.23\%yr^{-1}$ (± 0.24); D_{peak}=4.64% (± 4.79); D_{start}=1968 ; D_{end}=1988
		R^2=0.989; R^2_{adj}=0.987; MSE =0.1%; SSE=7.58%

Figure 9.14: Final improvement function model for the men's 1,000 m speed skating event

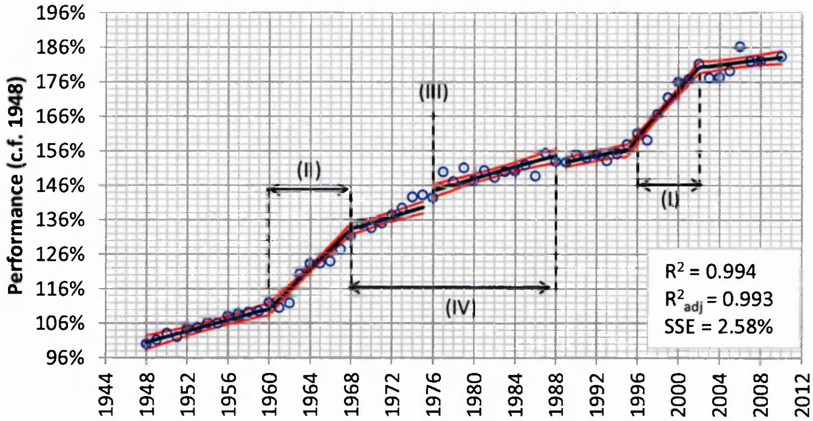
Men's 1,500 m speed skating long course



	Intervention	Parameters
	Global improvement	L=165.87% (± 16.04); a=0.006334 (± 0.009507); b=17.5060 (± 13.34)
I	Clap skate	$LU1=2.31\%yr^{-1}$ (± 0.68); $LU1_{peak}$=16.17% (± 4.78); $LU1_{start}$=1996 ; $LU1_{end}$=2002
II	Artificial ice	$LU2=0.86\%yr^{-1}$ (± 0.56); $LU2_{peak}$=6.85% (± 4.46); $LU2_{start}$=1960 ; $LU2_{e1nd}$=1968
III	Skin suit	k_1=103.94% (± 2.67); k_1year=1976
IV	Stricter drug testing	k_2=96.60% (± 2.67); k_2year=1989
V	Winter Olympic Games	Amp A=1.31% (± 0.82)
		R^2=0.992; R^2_{adj}=0.991; MSE =0.06%; SSE=2.98%

Figure 9.15: Final improvement function model for the men's 1,500 m speed skating event

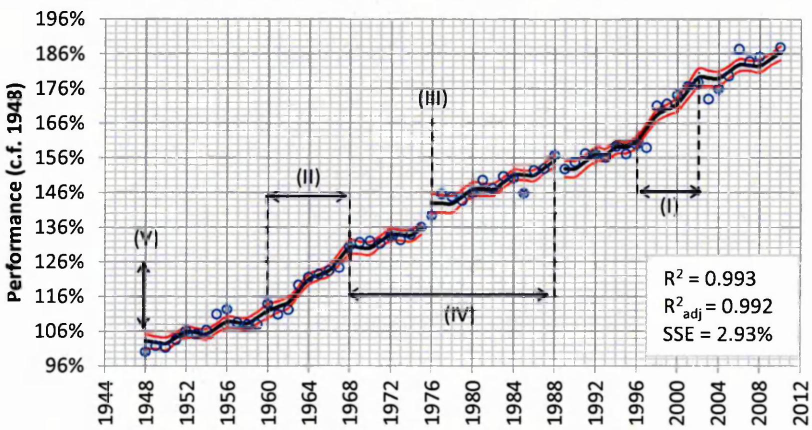
Men's 3,000 m speed skating long course



	Intervention	Parameters
	Global improvement	L=146.66% (± 12.74); a=0.028255 (± 0.02717); b=9.3566 (± 9.36)
I	Clap skate	$LU1=2.80\%yr^{-1}$ (± 0.57); $LU1_{peak}$=19.61% (± 4.01); $LU1_{start}$=1996 ; $LU1_{end}$=2002
II	Artificial ice	$LU2=2.05\%yr^{-1}$ (± 0.53); $LU2_{peak}$=16.41% (± 4.22); $LU2_{start}$=1960 ; $LU2_{e1nd}$=1968
III	Skin suit	k_1=102.81% (± 2.41); k_1year=1976
IV	Uptake of drugs before stricter drug testing	$D=0.12\%yr^{-1}$ (± 0.14); D_{peak}=2.48% (± 2.83); D_{start}=1968 ; D_{end}=1988
		R^2=0.994; R^2_{adj}=0.993; MSE =0.05%; SSE=2.58%

Figure 9.16: Final improvement function model for the men's 3,000 m speed skating event

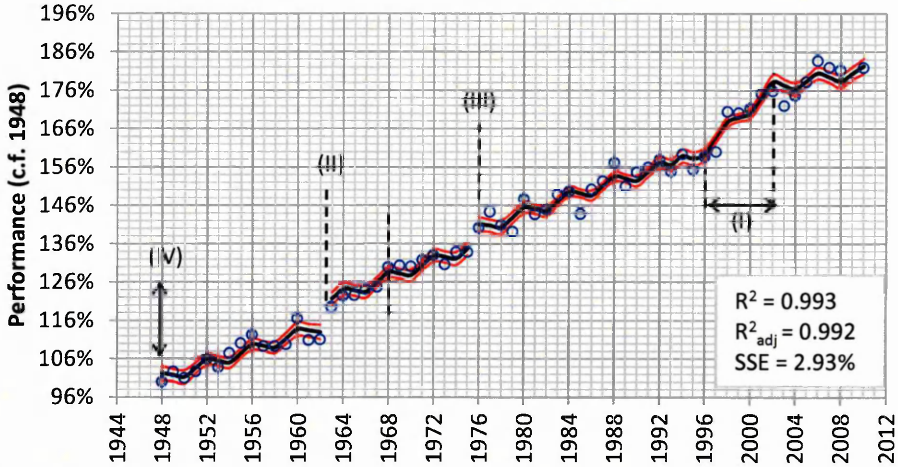
Men's 5,000 m speed skating long course



	Intervention	Parameters
	Global improvement	L=173.87% (± 18.33); a=0.005804 (± 0.01059); b=15.3801 (± 12.75)
I	Clap skate	$LU1=1.70\%yr^{-1}$ (± 0.68); $LU1_{peak}$=11.89% (± 4.74); $LU1_{start}$=1996 ; $LU1_{end}$=2002
II	Artificial ice	$LU2=1.46\%yr^{-1}$ (± 0.54); $LU2_{peak}$=11.67% (± 4.37); $LU2_{start}$=1960 ; $LU2_{e1nd}$=1968
III	Skin suit	k_1=103.90% (± 2.53); k_1year=1976
IV	Stricter drug testing	k_2=98.52% (± 2.24); k_2year=1989
V	Winter Olympic Games	Amp A=1.03 (± 0.81)%
		R^2=0.993; R^2_{adj}=0.992; MSE =0.05%; SSE=2.93%

Figure 9.17: Final improvement function model for the men's 5,000 m speed skating event

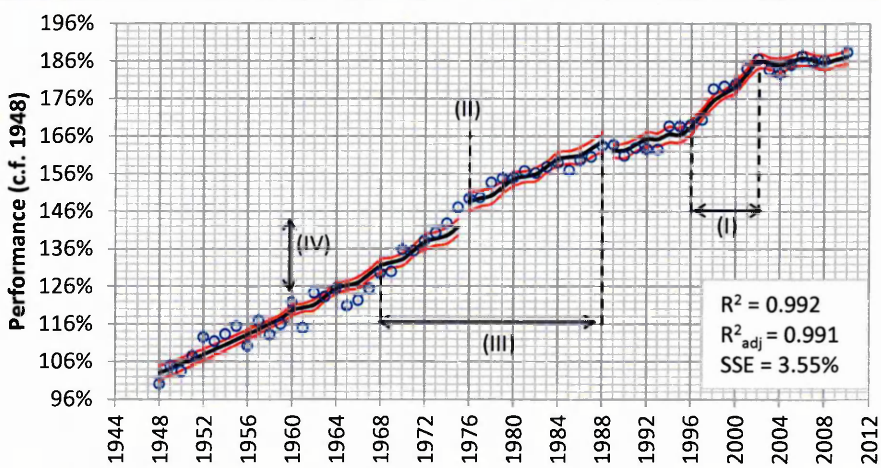
Men's 10,000 m speed skating long course



	Intervention	Parameters
	Global improvement	L=158.53% (± 8.55); a=0.008424 (± 0.007409); b=16.8538 (± 8.99)
I	Clap skate	$LU1=1.78\%yr^{-1}$ (± 0.59); $LU1_{peak}$=12.49% (± 4.10); $LU1_{start}$=1996 ; $LU1_{end}$=2002
II	Artificial ice	k_1=105.43% (± 2.81); k_1year=1963
III	Skin suit	k_2=102.81% (± 2.22); k_2year=1976
IV	Winter Olympic Games	Amp A=1.39% (± 0.76)
		R^2=0.993; R^2_{adj}=0.992; MSE =0.05%; SSE=0.47%

Figure 9.18: Final improvement function model for the men's 10,000 m speed skating event

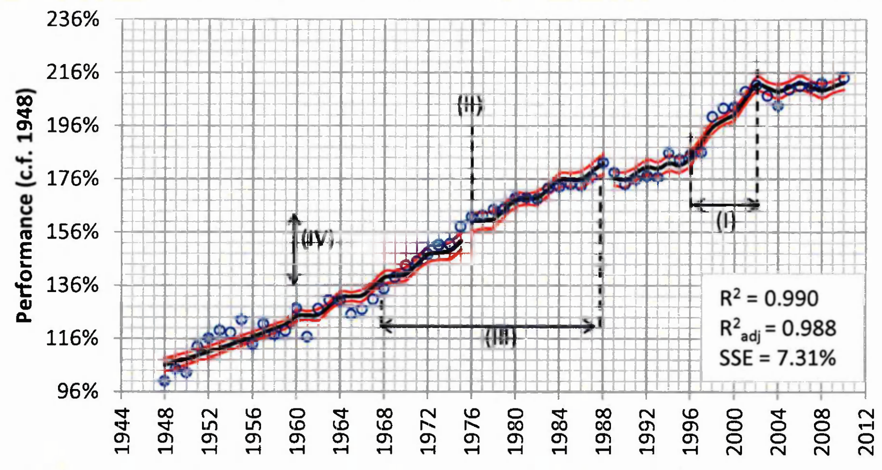
Women's 500 m speed skating long course



	Intervention	Parameters
	Global improvement	L=165.44% (± 6.98); a=0.001142 (± 0.0008125); b=58.3486 (± 22.72)
I	Clap skate	$LU1=2.23\%yr^{-1}$ (± 0.51); $LU1_{peak}$=15.58% (± 3.57); $LU1_{start}$=1996 ; $LU1_{end}$=2002
II	Skin suit	k_1=103.19% (± 2.83); k_1year=1976
III	Uptake of drugs before stricter drug testing	$D=0.13\%yr^{-1}$ (± 0.17); D_{peak}=2.52% (± 3.44); D_{start}=1968 ; D_{end}=1988
IV	Winter Olympic Games	Amp, A=0.71% (± 0.98)
		R^2=0.992; R^2_{adj}=0.991; MSE =0.07%; SSE=3.55%

Figure 9.19: Final improvement function model for the women's 500 m speed skating event

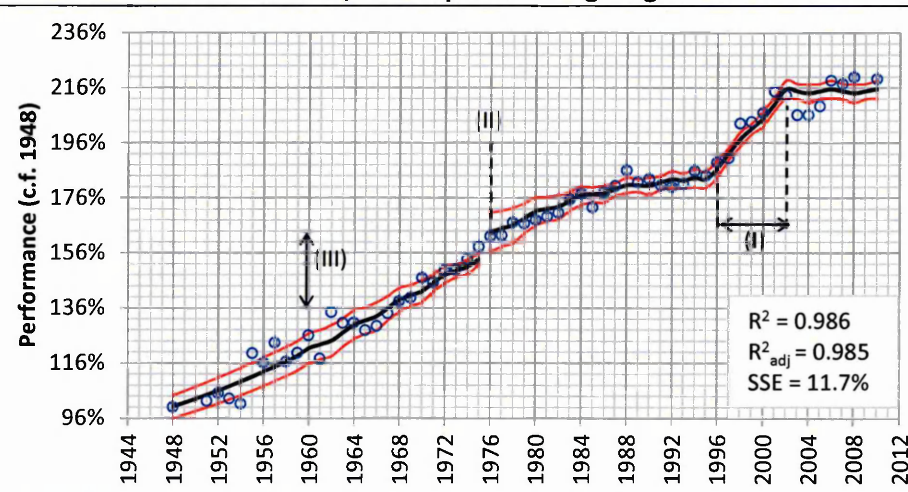
Women's 1,000 m speed skating long course



Intervention		Parameters
	Global improvement	L=180.41% (± 8.20); a=0.0001296 (± 0.0001868); b=186.3294 (± 144.22)
I	Clap skate	$LU1=3.70\%yr^{-1}$ (± 0.65); $LU1_{peak}$=25.87% (± 4.56); $LU1_{start}$=1996 ; $LU1_{end}$=2002
II	Skin suit	k_1=102.25% (± 3.89); k_1year=1976
III	Uptake of drugs before stricter drug testing	$D=0.26\%yr^{-1}$ (± 0.25); D_{peak}=5.19% (± 5.04); D_{start}=1968 ; D_{end}=1988
IV	Winter Olympic Games	Amp, A=1.47% (± 1.42)
		R^2=0.990; R^2_{adj}=0.988; MSE =0.1%; SSE=7.31%

Figure 9.20: Final improvement function model for the women's 1,000 m speed skating event

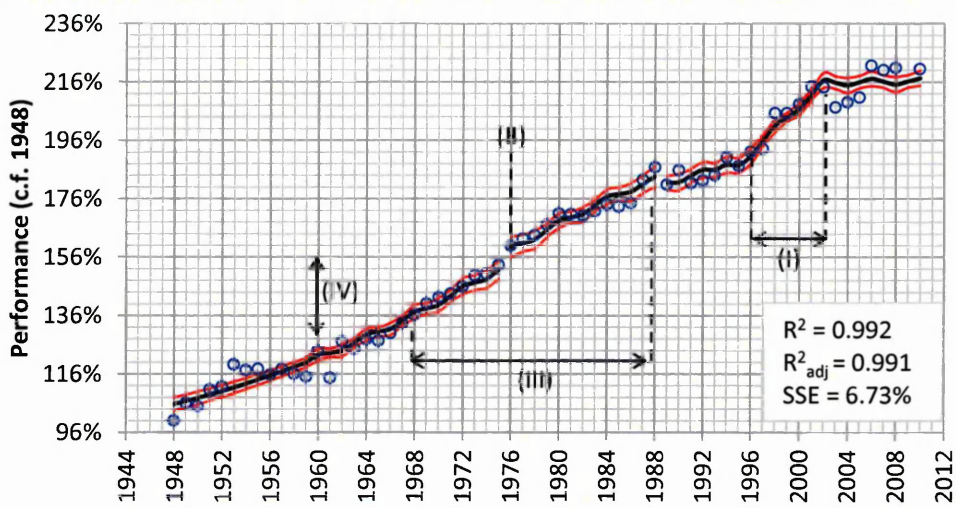
Women's 1,500 m speed skating long course



Intervention		Parameters
	Global improvement	L=175.40% (± 8.84); a=0.00002820 (± 0.00005331); b=507.4539 (± 484.09)
I	Clap skate	$LU1=4.30\%yr^{-1}$ (± 0.62); $LU1_{peak}$=30.13% (± 4.36); $LU1_{start}$=1996 ; $LU1_{end}$=2002
II	Skin suit	k_1=104.50% (± 4.67); k_1year=1976
III	Winter Olympic Games	Amp, A=0.70% (± 1.73)
		R^2=0.986; R^2_{adj}=0.985; MSE =0.2%; SSE=11.70%

Figure 9.21: Final improvement function model for the women's 1,500 m speed skating event

Women's 3,000 m speed skating long course



Intervention		Parameters
	Global improvement	L=185.70% (± 7.25); a=0.000043 (± 0.00007254); b=322.3439 (± 295.78)
I	Clap skate	$LU1$=3.51%yr^{-1} (± 0.64); $LU1_{peak}$=24.51% (± 4.49); $LU1_{start}$=1996 ; $LU1_{end}$=2002
II	Skin suit	k_1=102.92% (± 3.82); $k_1 year$=1976
III	Uptake of drugs before stricter drug testing	D=0.12%yr^{-1} (± 0.24); D_{peak}=2.49% (± 4.79); D_{start}=1968 ; D_{end}=1988
IV	Winter Olympic Games	Amp, A=0.99% (± 1.36)
		R^2=0.992; R^2_{adj}=0.991; MSE =0.1%; SSE=6.73%

Figure 9.22: Final improvement function model for the women's 3,000 m speed skating event

9.10 Results - Interventions modelled

9.10.(a) Artificial ice intervention

The first intervention that is going to be quantified is the effect of the introduction of better ice formation techniques used to reduce the coefficient of friction between the skate blade and the ice. Where a linear peak model was found to fit the performance data the linear peak effect is shown in Table 9.5. Where a step change model was found to fit performance data the best the step change parameter effect is shown in Table 9.6. Both the step change and linear peak used to model of ice developments are shown graphically in Figure 9.23, with cross hatched shading depicting the step change model effect.

9.10.a.(i) Results – artificial ice

Table 9.5: The magnitude of the linear peak changes accounting for the of uptake of better artificial ice formation in speed skating events where and effect could be measured

Gender	Event	Linear peak (PII)	+/-	Linear peak (s)	+/-
Men	500 m	2.01%	3.17%	-0.44	0.69
	1000 m	19.72%	6.80%	-9.07	3.00
	1500 m	6.85%	4.46%	-4.76	3.05
	3000 m	16.41%	4.22%	-24.08	5.97
	5000 m	11.67%	4.36%	-29.26	10.65

Table 9.6: The magnitude of the step change accounting for the of uptake of better artificial ice formation in speed skating events where and effect could be measured

Gender	Event	Step change (PII)	+/-	Step change (s)	+/-
Men	10000 m	5.43%	2.81%	-28.75	14.69

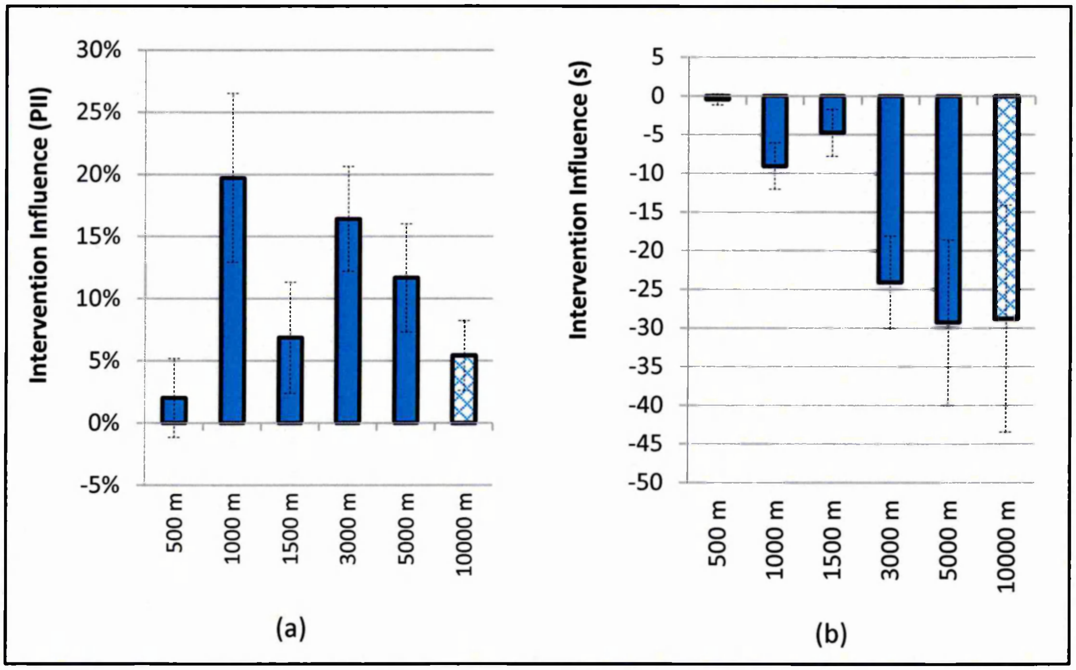


Figure 9.23: The magnitude of the linear peak and step change accounting for the uptake of better artificial ice formation in the speed skating events where and effect could be measured shown in units of (a) percentage improvement in the performance improvement index and (b) reduction of race time in seconds (NB step change magnitudes have been shown in the graph as crosshatched shading)

9.10.a.(ii) Discussion – artificial ice

The artificial ice development appears to have had the least influence in the men's 500 m speed skating event, albeit with high confidence intervals at 2.01 (+/- 3.17)%, -0.44 (+/-0.69) s . The confidence intervals are higher than the effect, again making it hard to gauge whether there is an effect at all. Artificial ice could have had the least effect in the 500 m men's event because this is the shortest sprint event, with a dominate acceleration phase so that the athlete is can attain the highest maximum speed. In the 500 m efficient gliding which saves energy is not as important as high energy expenditure which produces the highest acceleration and highest speed with continued pushing off strokes. Therefore the benefits from a reduced friction between the skate blade and the new lower friction ice may not be as influential. The greatest effect from artificial ice developments was in the in the men's 1,000 m event at 19.72 (+/-6.80) %, -9.07 (+/- 3.00) seconds. The 1,000 m event is on average the fastest event and twice as long as the 500 m, meaning the acceleration phase is still influential but not as important as maintaining the maximum speed through efficient gliding and energy conservation. This may mean in events of 1000 m and greater in distance, gliding strokes, biomechanical efficiency and energy conservation is more important and therefore the influence of friction reduction is greater.

Artificial ice developments was not modelled in the women's 1,500 m and 3,000 m as the goodness of fit value for the improvement function did not increase; however, the effect was found in all other events including the women's 500/1000 m. After closer examination of the fitting stages of the improvement function it appears that the global improvement model in the women's 1500 and 3000 m measures an uptake period, or slow acceleration of performances at the start of the historic period examined, meaning they do not conform to the standard exponential decay function like other events. This means the step change or linear uptake for ice development cannot be accurately gauged as these events appear to have an uptake period from 1948 which has been inadvertently modelled through the global improvement exponential function. In addition to this there appears to be a large increase in performance in the women's 1,500/3,000 m in the 1950s which is not accounted for with any modelling function. The increase in performance during this period could be due part of an uptake period of women's speed skating, and a large natural improvement in performance. The unaccounted intervention which occurs in the 1950s highlights the issue with modelling interventions techniques in that all interventions need to be accounting for to accurately gauge the effect of each intervention.

A step change intervention function was used to account for the development of artificial ice in the men's 10,000 m men event. This may just mean that the introduction of artificial ice had a more instantaneous effect in this event which could not be modelled through a linear uptake function.

9.10.a.(iii) Conclusion – artificial ice

In conclusion artificial ice development appears to have had a significant influence in almost all events. An ice development effect was not modelled in the women's 1500 and 3,000 m as the goodness of fit values did not increase. It appears this was down to the unusual shape of the global improvement function and possible linear improvement of speed skating, due to another factor such as a competing population increase which was not accounted for in this study.

The shortest men's event, the 500 m, appears to be influenced the least by artificial ice developments and this could be down to the nature of the event. Energy conservation and efficient gliding is not as important as all out speed and power in the 500 m event. Therefore efficiency gains from reduced friction may not be as beneficial as in longer distance events such as the 1,000 m and above, where energy conservation and skating efficiently is more important.

9.10.(b) Skin suits intervention: step change

9.10.b.(i) Results – Skin suits

The step change parameters accounting for the introduction of skin suits, aimed at reducing drag in 1976 for all speed skating events where an effect could be measured, are shown in Table 9.7 and graphically in Figure 9.24.

Table 9.7: The magnitude of the step changes accounting for the introduction of skin suits in speed skating events where and effect could be measured

Gender	Event	Step change (PII)	+/-	Step change (s)	+/-
Men	500 m	0.78%	1.97%	-0.17	0.43
	1000 m	5.96%	4.15%	-2.83	1.94
	1500 m	3.94%	2.67%	-2.76	1.85
	3000 m	2.81%	2.41%	-4.25	3.63
	5000 m	3.90%	2.53%	-9.95	6.40
	10000 m	2.82%	0.76%	-15.02	11.76
Women	500 m	3.19%	2.84%	-0.82	0.73
	1000 m	2.25%	3.89%	-1.22	2.11
	1500 m	4.50%	4.67%	-3.80	3.90
	3000 m	2.92%	3.82%	-5.24	6.80

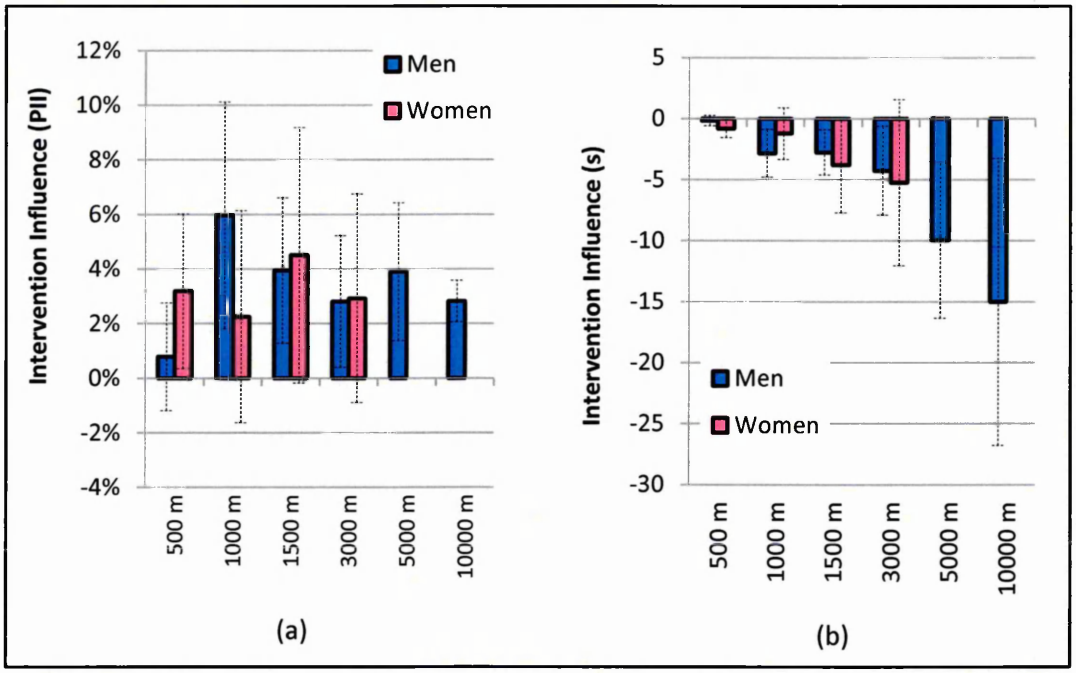


Figure 9.24: The magnitude of the step changes accounting for the introduction of skin suits in the speed skating events where and effect could be measured shown in units of (a) percentage improvement in the performance improvement index and (b) reduction of race time in seconds

9.10.b.(ii) Discussion – Skin suits

There appears to be a skin suit effect on speed skating performance in the majority of events; however an effect could not be modelled in the women's 500 and 1,000 m. This again could be down to not accounting for all interventions, or the unusual shape of the global improvement trend in these events which meant a step change in 1976 could not be found. This could be a sign of a conflict in the intervention modelling technique, in that a function to account for one intervention interferes with another function. This appears to be an inherent problem with the modelling techniques derived for this study.

The greatest skin suits effect was found in the men's 1,000 m at 5.96 (+/- 4.15) % or -2.83 (+/-1.94) seconds. This is the fastest event and could signify that the skin suits had the more of an effect in the faster event. The skin suit increases the skater's efficiency by reducing aerodynamic drag allowing more energy to be used to propel the skater forwards. The lowest modelled effect from skin suits was in the 500 m at 0.78(+/-1.97) % or -0.17(+/-0.43) seconds. Again the skin suit effect could be lowest in this event for similar reasons to the lower friction of newly developed ice, in that the 500 m is predominantly an accelerating event, with participants aiming to get to the fastest speed, with less emphasis put on energy preservation or maintaining the fastest speed for an extended period of time. There are high error bounds for all skin suit interventions modelled making it difficult to confidently say there is a true effect from skin suit introduction at all.

9.10.b.(iii) Conclusion – Skin suits

The effect of skin suits appears to have had a positive effect on speed skating performance; however the confidence intervals are high and in some cases larger than the magnitude of the effect. This makes it difficult to quantify and judge the true nature of the intervention. This could be due to problems with modelling multiple interventions and conflicts in terms. The suit effect appears to be the greatest in the men's 1000 m and lowest in the 500 m, this could be down to the 500 m race being dominated by an accelerating phase and not concerned with energy preservation. In contrast the 1000 m is competed at a higher speed for longer, meaning this event requires more energy preservation and the ability to maintain the highest speed for longer.

9.10.(c) Clap skates intervention: linear uptake

9.10.c.(i) Results – Clap skates

The next intervention modelled was the linear uptake of clap skate technology from 1996 to 2002. The peak influence of the linear uptake model accounting for the adoption of claps skates in speed skating for each event examined is shown in Table 9.8 and represented graphically in Figure 9.25.

Table 9.8: The magnitude of the linear uptake accounting for the clap skates technology taken up in from 1996 to 2002 for each different speed skating event

Gender	Event	Linear peak change (PII)	+/-	Linear peak (s)	+/-
Men	500 m	9.94%	2.97%	2.12	0.62
	1000 m	16.54%	7.04%	7.66	3.14
	1500 m	16.17%	4.78%	10.99	3.13
	3000 m	19.61%	4.01%	28.59	5.59
	5000 m	11.89%	4.74%	29.80	11.57
	10000 m	12.49%	4.10%	65.07	20.76
Women	500 m	15.58%	3.57%	3.90	0.86
	1000 m	25.87%	4.56%	13.34	2.22
	1500 m	30.13%	4.36%	24.04	3.26
	3000 m	24.51%	4.49%	41.81	7.26

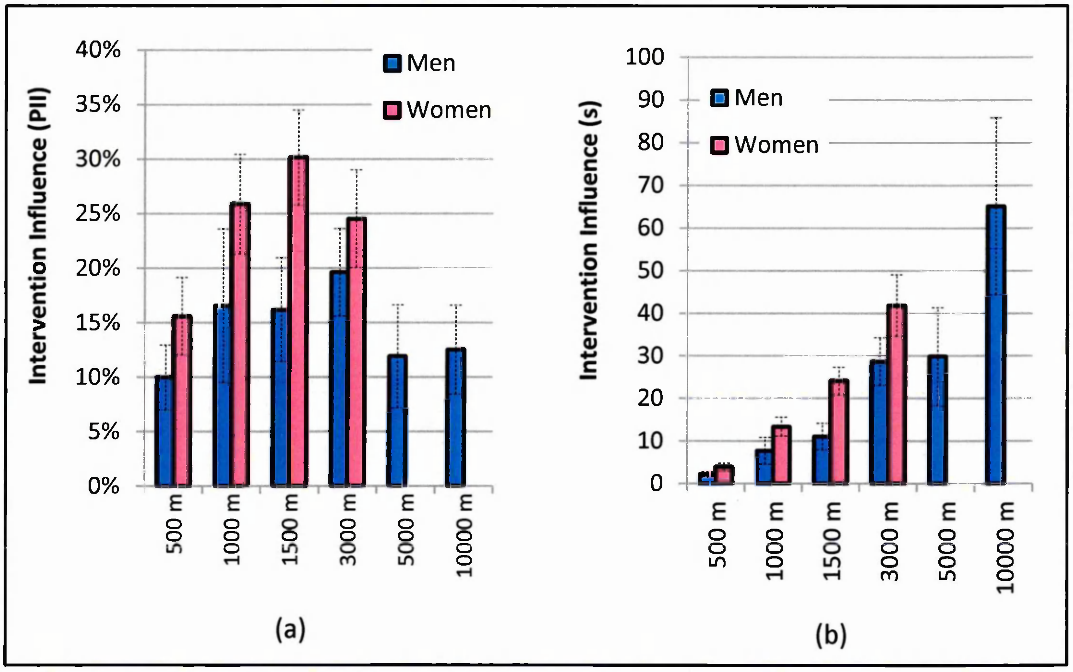


Figure 9.25: The magnitude of the linear uptake accounting for the clap skates technology taken up in from 1996 to 2002 for each different speed skating event shown in units of (a) percentage improvement in the performance improvement index and (b) reduction of race time in seconds

9.10.c.(ii) Discussion – Clap skates

There appears to be a definite positive clap skate effect in all events as all error bounds are significantly smaller than the modelled influence. The clap skate effect appears to be generally greater in women's events than in comparable men's event. The women's 1,500 m is influenced to the greatest extent from clap skate adoption, at 30.13 (+/- 4.36) % or a drop in time of 24.04 (+/- 3.26) seconds. The greatest effect in the men's event is in the 3,000 m at 19.61 (4.01) % or 28.59 (+/-5.59) %. The least influence was seen in the men's and women's 500 m at 9.94 (+/- 2.97) and 18.69 (+/- 3.67) % respectively. The higher influence seen from clap skates in women's event when compared to men's events is in contrast to the other intervention measured so far in speed skating events. This could mean that clap skates are more beneficial to women speed skaters, and that something unique to female anatomy enables greater performance gains over fellow male competitors. Generally it also appears that there is a similar magnitude in the clap skate effect for each gender in all the events.

However an interesting trend becomes apparent when plotting the increase in speed (taking 2010 as baseline time) due to clap skates against event distance, which is shown in Figure.9.26. Trend lines have been drawn on by hand, are not calculated from a function and are therefore to be used simply as a guide. Using the trend line it appears that the men's 1,500 m event is slightly lower than expected, but still the line falls within the confidence regions. The trend line reveals that the clap skate introduction had the same change in effect in terms of speed in the men's 500, 5000 and 10000 m event at around 1 ms^{-1} increase. Similarly for the 1000m, 1500 m and 3,000 m men's events the increase in speed is about 1.5 ms^{-1}. A similar trend appears evident in women's events, but with a greater increase in speed.

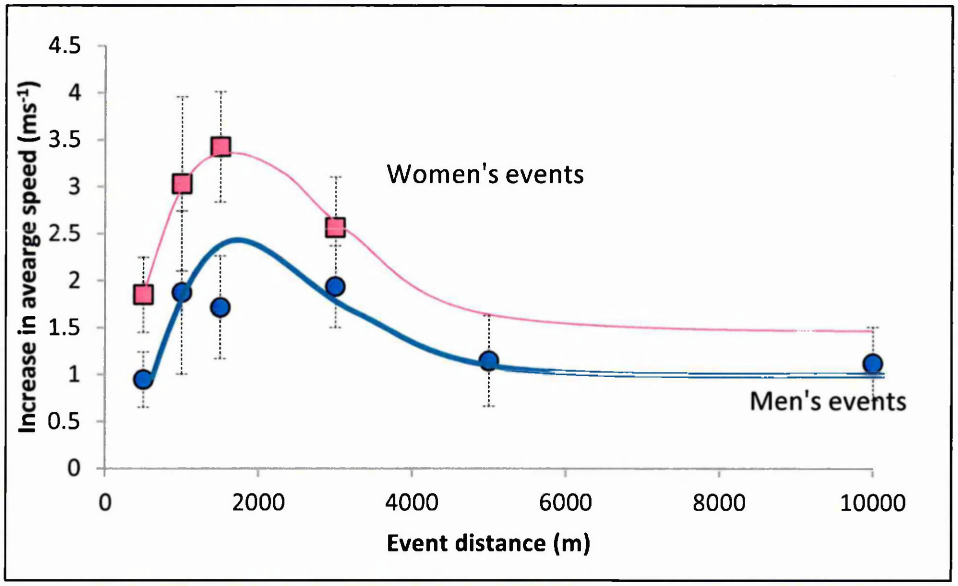


Figure.9.26: The increase in average speed as a result of the adoption of clap skates had for each different speed skating event distance

Clap skates are believed to increase the maximum speed of the skater through increased biomechanical efficiency. However the increase in speed in the 500 m may be low because the clap skates are likely not to increase the acceleration of the speed skater. As the 500 m event is dominated by the acceleration phase, attaining a greater increase in maximum speed above the 1ms^{-1} from clap skates is not possible.

The effect of clap skates is also low in the 5,000 and 10,000 m. This is likely due to the energy restraints of human metabolism, as energy must be produced for an extended period of time with subsequent reliance on the anaerobic system. This means there is a ceiling for the increase in speed due to efficiency gains from clap skates, and this has been measured at about a 1ms^{-1}.

Clap skates increased the maximum attainable speeds and their effect is most noticeable in the fastest events; these are the 1,000 m, 1,500 and 3,000 m. This is likely down to the nature of these events, where maintaining the greatest speed over the duration of the race is dominant in determining performance, illustrated by the high average speeds of these races. The clap skate in these events is likely to have increased the maximum speed of the speed skater.

9.10.c.(iii) Conclusion – Clap skates

In conclusion clap skates certainly have had a positive influence on speed skating performance in all events. Women's events appear to be influenced to a greater extent when compared to men's events, and this is likely secondary to inherent physiological differences between men and women. This allows greater efficiency gains to be made for female athletes when compared to male athletes.

Clap skates increase the maximum speed of the skater through increased biomechanical efficiency. This increased efficiency allows sufficient an energy-saving to be made in the long distance events, the 5000 m and 10000 m men's events, which has the effect of increasing the speed in these events of about 1 ms^{-1}. The greater attainable speeds due to clap skates could not be utilised in these long distance events, but in the 1000 m, 1500 m and 3000 m events the clap skates are likely to achieve a greater maximum speed, and thus the greatest effects from clap skates are more prominent in these events. The 500 m experiences a lower influence from clap skates, and this may due to the dominant effect on the race by the acceleration phase, and the lack of time available to utilise the full effect of obtaining greater speeds.

9.10.(d) Drugs interventions: linear uptake and step change

9.10.d.(i) Results – Drugs

The influence of performance-enhancing drugs (and drug testing) has been modelled through the use of a linear uptake model from 1968 to 1988, followed by a step change in 1989 accounting for better drug testing techniques. The magnitude of the drugs peak in events where a linear uptake was found to model the uptake of drugs is shown in Table 9.9. Where a linear uptake model did not improve the fit of the improvement function, a single step change in 1989, accounting for better drug testing, was used. The magnitude of the individual step change in 1989 is shown Table 9.10. Both the step change and linear peak used to model of the effect of drug interventions are shown graphically in Figure 9.27, with cross hatched shading depicting the step change model effects.

Table 9.9: The magnitude of the linear peak (1968-1988) before a step change accounting for the of uptake of better drugs and better drug testing technology in 1989

Gender	Event	Drugs peak (PII)	+/-	Drugs peak (s)	+/-
Men	500 m	2.42%	2.12%	0.53	0.46
	1000 m	4.64%	4.79%	2.21	2.26
	3000 m	2.48%	2.83%	3.76	4.27
Women	500 m	2.52%	3.44%	0.65	0.88
	1000 m	5.19%	5.04%	2.81	2.69
	3000 m	2.49%	4.79%	4.46	8.54

Table 9.10: The magnitude of the step change in 1989 accounting drug testing technology in 1989

Gender	Event	Step change (PII)	+/-	Step change (s)	+/-
Men	1500 m	3.40%	2.27%	2.42	1.63
	5000 m	1.48%	2.24%	3.83	5.82

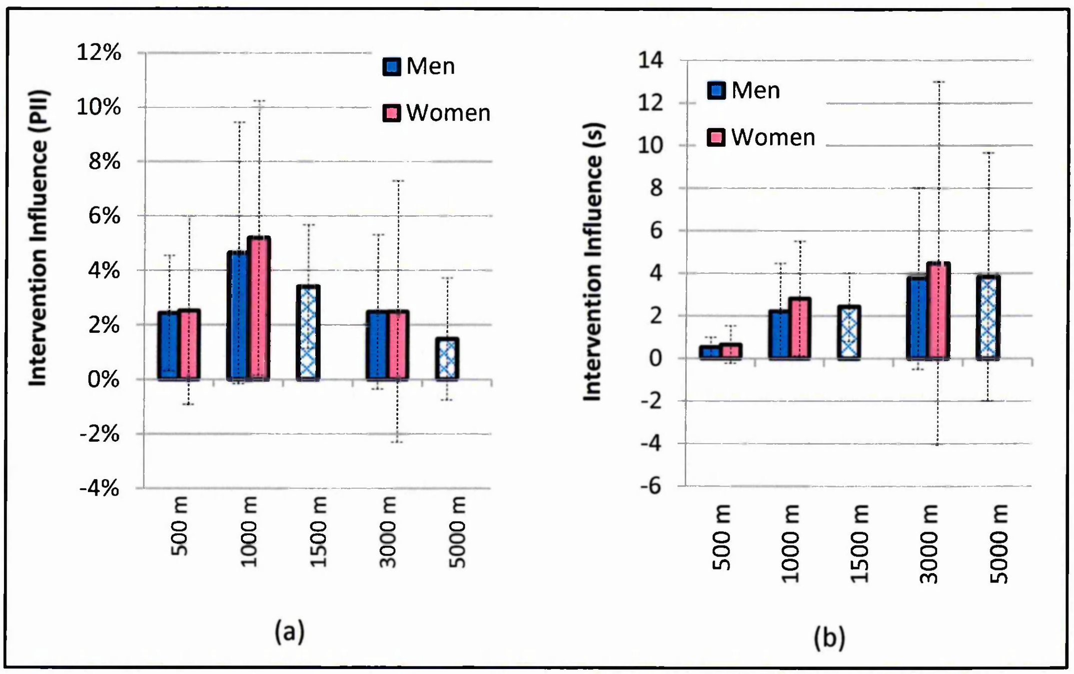


Figure 9.27: The magnitude of the linear peak (1968-1988) before a step change and an individual step change (1989) accounting for the uptake of drugs and better drug testing procedures in the speed skating events where and effect could be measured, shown in units of (a) percentage improvement in the performance improvement index and (b) reduction of race time in seconds (NB step change magnitudes have been shown in the graph as crosshatched shading)

9.10.d.(ii) Discussion – Drugs

A drugs linear uptake with a step change in 1989 was found in the majority of events. Additionally a step change without a linear uptake was found in only a couple of events, the men's 1,500 m and 5,000 m. The greatest influence from a modelled drugs using this step change is seen in the 1,000 m men and women at 4.64 (+/-4.79) % and 6.79 (+/- 5.92) % respectively. Women's speed skating events appear to have been subject to a similar albeit a slightly greater influence from drugs overall when compared to men's events. Generally the modelled effect of drugs in speed skating is small, when compared to other athletic events. Additionally, there are large confidence bounds which again make it difficult to ascertain whether there is any effect from drugs at all. All events except the women's 1,000 m and men's 1,500 m have confidence regions larger than the modelled effect. Drugs may not be as prominent in speed skating as in other athletic events as it hard to see a definite effect.

9.10.d.(iii) Conclusion – Drugs

In conclusions a drugs effect in speed skating is not prominent and it is difficult to gauge any effect at all due to the large confidence bounds. The greatest effect appears to be in the 1,000 m for both men and women. Unlike other athletic events the effect of drugs in speed skating seems to at a comparable level for both men's and women's events.

9.10.(e) Olympic influence:

9.10.e.(i) Results – Olympic influence

The final intervention to be modelled in the speed skating events is the Olympic effect, accounted for by a sine function with a period of 4 years, with a change in phase in 1994. The magnitude of the sine function and the maximum effect of the Olympic Games from peak to trough is shown in Table 9.11and represented graphically in Figure 9.28.

Table 9.11: The magnitude of the effect of the Olympics Games for each different speed skating event

Gender	Event	Olympics amplitude (PII)	+/-	Olympics amplitude (s)	+/-	Max effect (PII)	Max effect (s)
Men	500 m	0.95%	0.56%	0.21	0.12	3.02%	0.66
	1000 m	1.31%	0.82%	0.92	0.58	4.26%	3.00
	5000 m	1.03%	0.81%	2.64	2.08	3.67%	9.44
	10000 m	1.39%	0.76%	7.46	4.06	4.31%	23.02
Women	500 m	0.71%	0.98%	0.18	0.25	3.38%	0.88
	1000 m	1.47%	1.42%	0.80	0.77	5.77%	3.14
	1500 m	0.70%	1.73%	0.60	1.48	4.87%	4.15
	3000 m	0.99%	1.36%	1.78	2.43	4.69%	8.43

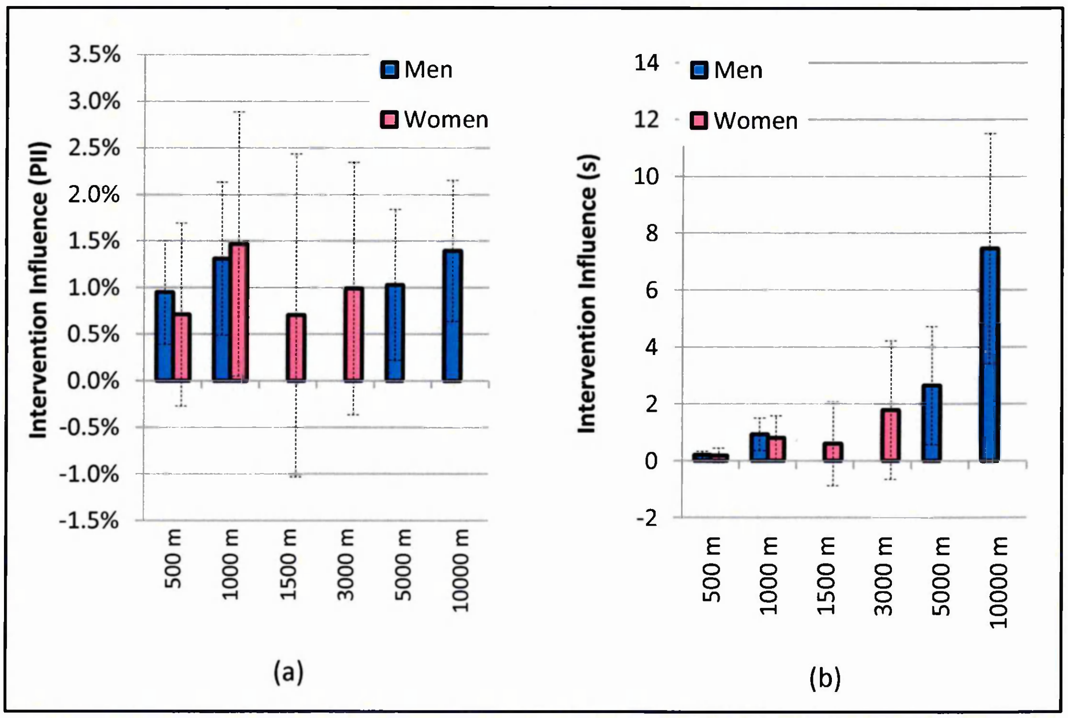


Figure 9.28: The magnitude of the effect of Olympics Games for each different speed event shown in units of (a) percentage improvement in the performance improvement index and (b) increase in race time in seconds

9.10.e.(ii) Discussion – Olympic influence

The Olympic sine function improves the fit in all events, but as with the modelled Olympic effect in other athletic events, the magnitude of the intervention is small from 0.70 % to 1.53 %. The Olympic effect is similar for all events and no trends can be seen for the different distances. The confidence intervals are also high and in the majority of events higher than the modelled influence. This makes it hard to confidently say there is a positive effect at all.

9.10.e.(iii) Conclusion – Olympic influence

In conclusion it is difficult to quantify the effect of the Olympic Games as the Olympic effect is small often with large confidence intervals. This is similar to the Olympic effects modelled in other athletic events.

9.10.(f) Limits to athletic performance

9.10.f.(i) Results – limits to athletic performance

The year at which the global exponential function is within 0.1 % of the limit (essentially reaching the predicted limit) is shown in Table 9.12 for all speed skating events examined.

Table 9.12: The predicted natural performance limits for all speed skating events examined shown with year at which the improvement functions are within 0.1% of this limit and shown with 95 % confidence bounds

Gender	Event	L parameter (PII %)	+/-	L parameter (s)	+/-	Year when within 0.1 % of limit
Men	500 m	147.72%	7.30%	35.92	0.89	2034
	1000 m	162.29%	21.81%	75.63	5.14	2048
	1500 m	165.87%	16.04%	109.66	5.33	2044
	3000 m	146.66%	12.74%	251.96	10.99	2046
	5000 m	173.87%	18.33%	391.07	20.75	2060
	10000 m	158.53%	8.55%	852.69	23.05	2038
Women	500 m	165.44%	6.98%	40.38	0.85	2015
	1000 m	180.41%	8.20%	81.44	1.85	2010
	1500 m	175.40%	8.84%	128.96	3.26	2000
	3000 m	185.70%	7.25%	264.83	5.18	2008

New limits of speed skating performance have been adjusted accordingly for interventions that are believed to be currently an influence on speed skating performance, and are shown in Table 9.13. The interventions which are believed to be influencing factors on speed skating performance are the development of artificial ice surfaces, the use of skin suits, the adoption of clap skates and also the effect of the Olympic Games. The step changes and linear uptakes accounting for drugs are believed not to have an influence on current and future speed skating performances.

Table 9.13: New predicted speed skating performance limits taking into account interventions since 1948

		L parameter		Artificial ice		Skin suits		Clap skates		Olympic Games		New limit with interventions	
Gender	Event	(PII %)	(s)	(PII %)	(s)	(PII %)	(s)	(PII %)	(s)	(PII %)	(s)	PII (%)	(s)
Men	500 m	147.72%	35.92	2.01%	-0.44	0.78%	-0.17	9.94%	-2.12	0.95%	-0.21	161.78%	32.98
	1000 m	162.29%	75.63	19.72%	-9.07	5.96%	-2.83	16.54%	-7.66	1.31%	-0.92	209.54%	55.14
	1500 m	165.87%	109.66	6.85%	-4.76	3.94%	-2.76	16.17%	-10.99			195.43%	91.16
	3000 m	146.66%	251.96	16.41%	-24.08	2.81%	-4.25	19.61%	-28.59			186.80%	195.04
	5000 m	173.87%	391.07	11.67%	-29.26	3.90%	-9.95	11.89%	-29.80	1.03%	-2.64	205.23%	319.42
	10000 m	158.53%	852.69	5.43%	-28.75	2.82%	-15.02	12.49%	-65.07	1.39%	-7.46	185.72%	736.39
Women	500 m	165.44%	40.38			3.19%	-0.82	18.69%	-4.64	0.79%	-0.21	190.19%	34.71
	1000 m	180.41%	81.44			2.25%	-1.22	26.84%	-13.81	1.53%	-0.84	212.84%	65.57
	1500 m	175.40%	128.96			4.50%	-3.80	30.13%	-24.04	0.70%	-0.60	214.12%	100.52
	3000 m	185.70%	264.83			2.92%	-5.24	24.51%	-41.81	0.99%	-1.78	216.63%	216.00

9.10.f.(ii) Discussion – limits to athletic performance

Projections show that men's speed skating events are unlikely yet to have reached a peak, with estimates of the year 2034 for seeing a peak in the 500 m. This indicates that currently male speed skating performances are continuing to improve, and that this trend is likely to continue for around the next 20 years. The driving force behind improvements in the men's event may well be an increase in the size of the competing population. The growth in popularity of speed skating and the building of new ice rinks has enabled the competing population to grow and encompass a greater percentage of the world's population. This also highlights the theory that speed skating may lag behind in the global improvement trend in comparison to other athletic events, and this difference is arguably the result of a smaller competing population. However in the women's event it appears that the modelled limits of performance have already been reached. and performances are not currently improving. This may be because there is no growth in the competition population. In addition to this it may be difficult to model the global improvement and the limits of performance in the women's events. This is because the year at which the limit is predicted to be reached is close to the linear uptake of clap skates. This means the predicted year at which a limit is reached may be affected. The collection of further performance results in future will be the only way to verify this. The women's speed skating events appear to have reached a limit in this study. However, this may not be there case as an intervention such as an increase in the competing population could increase the limits of performance in women's events.

The maximal levels of predicted performance improvement in all the speed skating events examined cover a similar range in both genders, indicating all events for specific genders start a similar level of competitiveness. For men the predicted improvement is between 47.72 % and 73.87 % and for the women it is between 74.32 % and 85.70 %. The slightly higher predicted improvement range in values for the women's events can be related back to the baseline performance figures, and that the women's events may have been less competitive than the men's events at the baseline performance year. The new maximal performance improvements taking into account the modelled interventions in the long course speed skating events vary between 61.78 and 116.63%. These figures indicate that there is large improvement above the original predicted performance improvement limits, indicating that the modelled interventions have contributed greatly to performance improvements in speed skating.

9.10.f.(iii) Conclusion – limits to athletic performance

In conclusion, the predicted limits of performance in the men's event are not yet believed to have been reached. This indicates that men's speed skating performances are continuing to evolve and improve, and this effect could be the result of an increasing trend in the size of the competing population. Conversely, the predicted limits of performance in the women's events have already been reached, and women's speed skating performances have stagnated. The principal reason for this may well be the static size of the competing population.

The magnitudes of the predicted original performance limits are similar for the gender groups but generally higher for the women. This indicates that for the gender groups all events are at a similar level at the base line year of 1948. The higher values for women are likely to indicate that women were less competitive at the base line year of 1948, and so can be predicted to improve more.

There is a significant influence from interventions in speed skating performances, as illustrated by the large change from the original predicted performance limits to new predicted limits once interventions are taken into account.

9.11 Chapter summary

Speed skating is the final athletic event to be examined to determine the effects of any intervention influence. Speed skating is the most modern athletic racing event to be included here, with competitions only having taken place from 18th century onwards. Consequently it is believed that speed skating competition levels in 1948 are lower than those of the other athletic events examined, and this is reflected in the high initial predicted limits of performance without interventions. The lower levels of development in speed skating in 1948 are attributable to a smaller competing population, due to restrictions in the location of suitable ice tracks before the invention of artificial ice and indoor ice rinks. Currently men's speed skating performance is predicted to increase but the women's performance has stagnated. This could be due to an increase in the competing population in men's events but not the women's. Women's speed skating performance may increase with an extra intervention such as an influx of a new competing population.

Speed skating appears to be highly influenced by external technologies; artificial ice developments and clap skates appear to be the dominant interventions. Skin suits and the Olympic Games have had a small influence on speed skating performance and it is difficult to say if there is a positive effect at all from these interventions. The greatest influence on speed skating performance other than the global improvement trend since 1948 appears to be the introduction and uptake of clap skates from 1996 up to 2002, at between 9.94 (+/- 2.97)% to 30.13 (+/- 4.36)% in the men's 500 m, and women's 1,500 m respectively. The Winter Olympic Games has the smallest effect on performance, from 0.70 (+/-1.73) % to 1.53 (+/-1.45) % in the women's 1,500 and 1,000 m respectively. The higher speeds of speed skating events along with the late development and the small initial size of the competing population may have all contributed to the large interventions modelled within this event. The breakdown of the influence from each individual intervention is summarised in Table 9.14.

Table 9.14: A summary of the intervention seen in all long course speed skating events examined

Event	Intervention gauged	Effect size (PII) %
Selected events	Development of artificial ice (1960-1968 or 1963 step)	2.01% -19.72%
Selected events	Skin suits, 1976	0.78% – 5.96%
All	Clap skate 1996 -2002	9.94% – 30.13%
Selected events	Drugs	1.48% – 6.78%
All	Olympics	0.70% – 1.53%
All	Original performance limit	47.72% – 85.70%
All	New performance improvement limit	61.78% – 116.63%

Chapter 10: Summary and conclusions

10.1 Introduction

Within the sports examined in this study athletic performance has been influenced by interventions to some extent. The most dominant of these interventions is theorised to be the increase in the size of competing population, arguably the greatest influencing factor behind the global improvement of all athletic performance. Technological interventions have also influenced athletic performance to a lesser extent. Some interventions are applicable to a wide range of sporting events, such as a measured drug or Olympic Games influence. Other interventions are event-specific such as the Fosbury Flop in the high jump, or clap skates in speed skating. Finally there are some interventions which have been eliminated through the introduction of rules or technology, and do not influence current sporting performance. Examples of these are the banning of full body swimming suits and the introduction of better drug testing procedures minimising drug use in sport. It has also been discovered that some interventions have had an unexpected negative influence upon measured athletic development, such as the introduction of fully automatic timing systems in racing events.

The entirety of interventions modelled within each sport examined within this project (running events, field events, freestyle swimming and speed skating) needs to be summarised and meaningful conclusions made. Additionally comparisons between the size of interventions and technology in different events are also required. The objectives of this final chapter are therefore are as follows:

1. To summarise the magnitude of all interventions upon overall sporting improvement
2. To summarise the influence of all interventions within each different sport
3. To comment on the level of technology and other intervention influence in each sporting event and make inter-event comparisons
4. To conclude what the effect of technology is on elite athletic sport
5. To discuss future work

10.2 Interventions which influence performance

The overall influence from all interventions currently believed to be influencing factors on the sporting events examined have been summarised in Figure 10.1. The red shaded bars indicate the overall intervention influence, and the blue spotted bars indicate the maximum predicted improvement in each event from 1948. This data is shown in tabular form in Table 10.1, and displays the influence from all interventions in terms of performance improvement and raw performance figures.

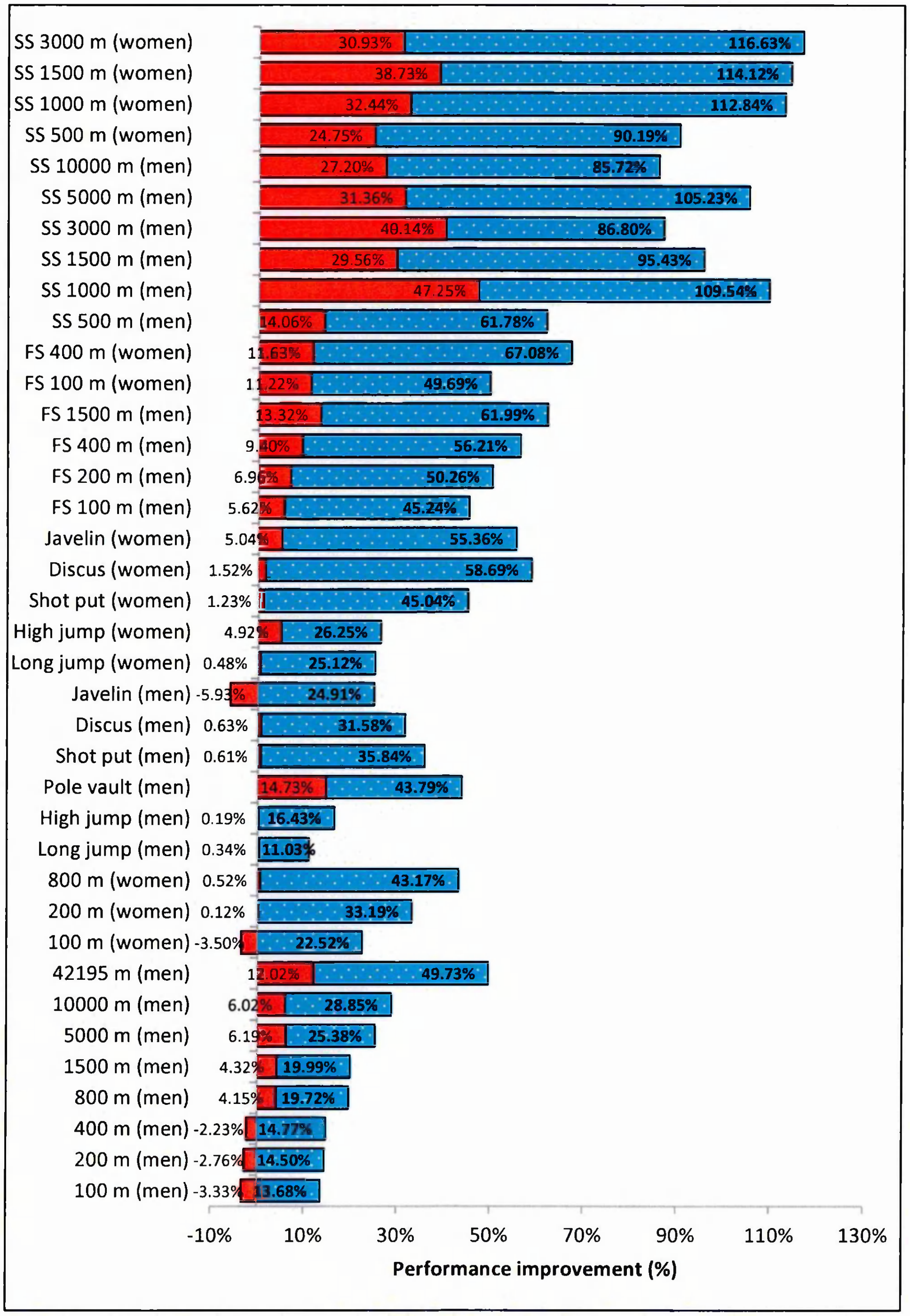


Figure 10.1: Overall size of influence all the interventions have in the different sports

Table 10.1: Size of all interventions, technology interventions and predicted maximum performance increase from 1948 shown in performance improvement and raw performance figures

Event	Limit of athletic performance (% increase from 1948)	Predicted limit of athletic performance accounting for interventions (% increase from 1948)	Overall interventions influence (% increase)	Interventions influence (seconds or metres)	Technology influence (% increase)	Technology influence (seconds or metres)
100 m (men)	17.01%	13.68%	-3.33%	0.15	-3.80%	0.20
200 m (men)	17.25%	14.50%	-2.76%	0.24	-2.72%	0.29
400 m (men)	17.00%	14.77%	-2.23%	0.42	-2.26%	0.54
800 m (men)	15.57%	19.72%	4.15%	-2.28	0.00%	0.00
1500 m (men)	15.67%	19.99%	4.32%	-4.94	0.00%	0.00
5000 m (men)	19.18%	25.38%	6.19%	-26.54	0.00%	0.00
10000 m (men)	22.83%	28.85%	6.02%	-54.74	0.00%	0.00
42195 m (men)	37.71%	49.73%	12.02%	-542.58	0.00%	0.00
100 m (women)	26.02%	22.52%	-3.50%	0.17	-3.04%	0.18
200 m (women)	33.07%	33.19%	0.12%	-0.03	-0.40%	0.05
800 m (women)	42.65%	43.17%	0.52%	-0.35	0.00%	0.00
Average	24.00%	25.95%	1.96%	-57.32	-1.11%	0.11
Long jump (men)	10.69%	11.03%	0.34%	0.03	0.00%	0.00
High jump (men)	16.24%	16.43%	0.19%	0.00	0.00%	0.00
Pole vault (men)	29.06%	43.79%	14.73%	0.49	11.07%	0.47
Shot put (men)	35.22%	35.84%	0.61%	0.07	0.00%	0.00
Discus (men)	30.95%	31.58%	0.63%	0.24	0.00%	0.00
Javelin (men)	30.84%	24.91%	-5.93%	-3.12	-4.74%	-3.26
Long jump (women	24.65%	25.12%	0.48%	0.02	0.00%	0.00
High jump (women	21.33%	26.25%	4.92%	0.06	3.69%	0.06
Shot put (women)	43.80%	45.04%	1.23%	0.11	0.00%	0.00
Discus (women)	57.17%	58.69%	1.52%	0.41	0.00%	0.00
Javelin (women)	50.33%	55.36%	5.04%	0.80	1.08%	0.48
Average	31.84%	34.00%	2.05%	-0.08	1.01%	-0.20
FS 100 m (men)	39.62%	45.24%	5.62%	-1.55	4.79%	-1.75
FS 200 m (men)	43.30%	50.26%	6.96%	-3.35	5.09%	-2.91
FS 400 m (men)	46.80%	56.21%	9.40%	-7.76	7.56%	-7.02
FS 1500 m (men)	48.68%	61.99%	13.32%	-67.36	11.59%	-62.26
FS 100 m (women)	38.47%	49.69%	11.22%	-3.73	10.75%	-4.70
FS 400 m (women)	55.46%	67.08%	11.63%	-16.42	9.74%	-15.07
Average	45.39%	55.08%	9.69%	-16.69	8.25%	-15.62
SS 500 m (men)	47.72%	61.78%	14.06%	-2.93	12.73%	-2.73
SS 1000 m (men)	62.29%	109.54%	47.25%	-20.49	42.22%	-19.57
SS 1500 m (men)	65.87%	95.43%	29.56%	-18.50	26.96%	-18.50
SS 3000 m (men)	46.66%	86.80%	40.14%	-56.92	38.83%	-56.92
SS 5000 m (men)	73.87%	105.23%	31.36%	-71.65	27.46%	-69.01
SS 10000 m (men)	58.53%	85.72%	27.20%	-116.30	20.73%	-108.84
SS 500 m (women)	65.44%	90.19%	24.75%	-7.80	30.36%	-7.59
SS 1000 m (women)	80.41%	112.84%	32.44%	-20.85	38.51%	-20.02
SS 1500 m (women)	75.40%	114.12%	38.73%	-28.44	34.63%	-27.84
SS 3000 m (women)	85.70%	116.63%	30.93%	-48.83	27.44%	-47.05
Average	66.19%	97.83%	31.64%	-39.27	29.99%	-37.81

The size of every intervention in each different sporting event has been broken down and illustrated in Figure 10.2. Following on from this the average effect from all interventions in each sporting category is represented graphically in in Figure 10.3, and this is compared to the technology only interventions.

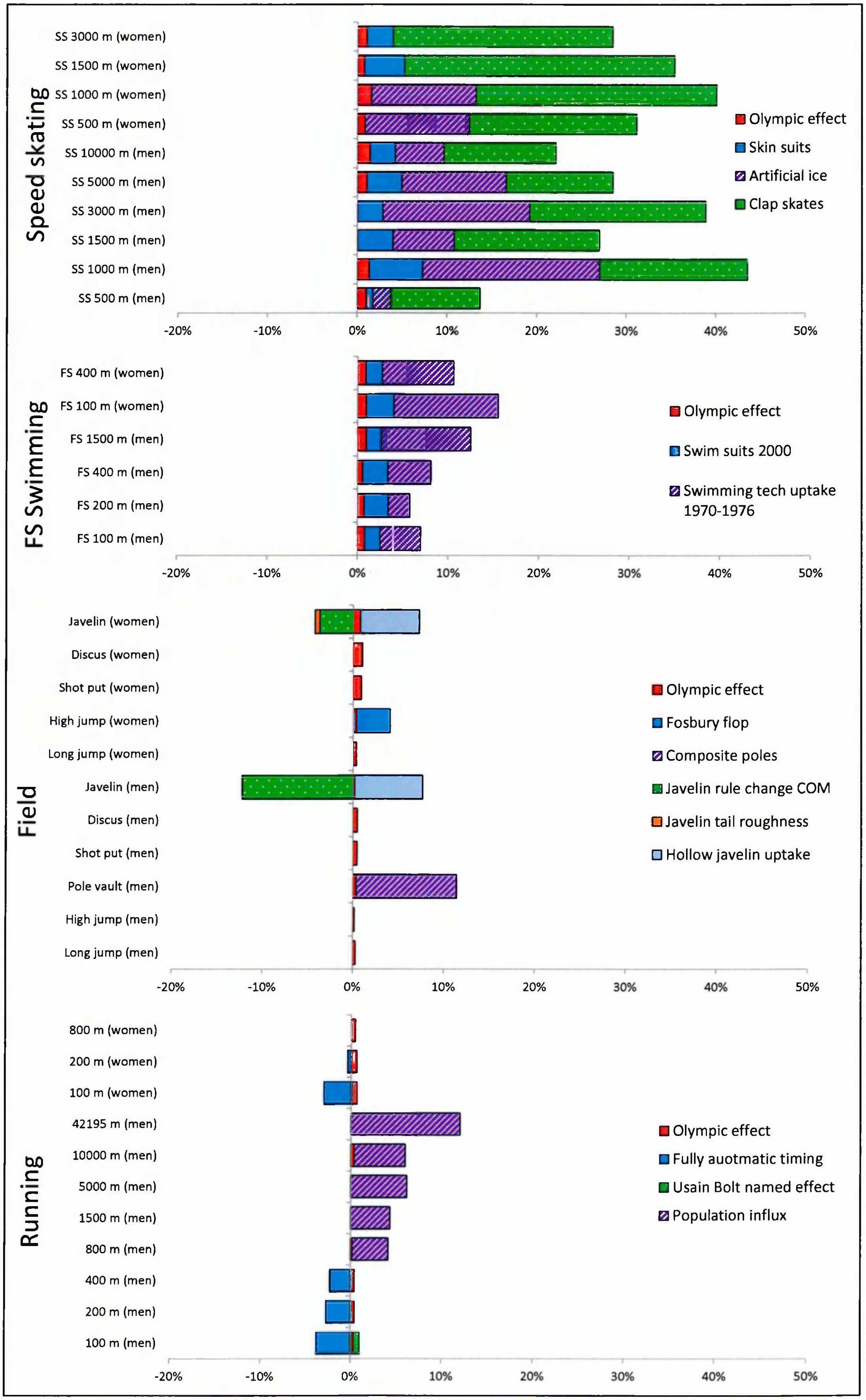


Figure 10.2: Breakdown of the size of influence each intervention has in the different sports

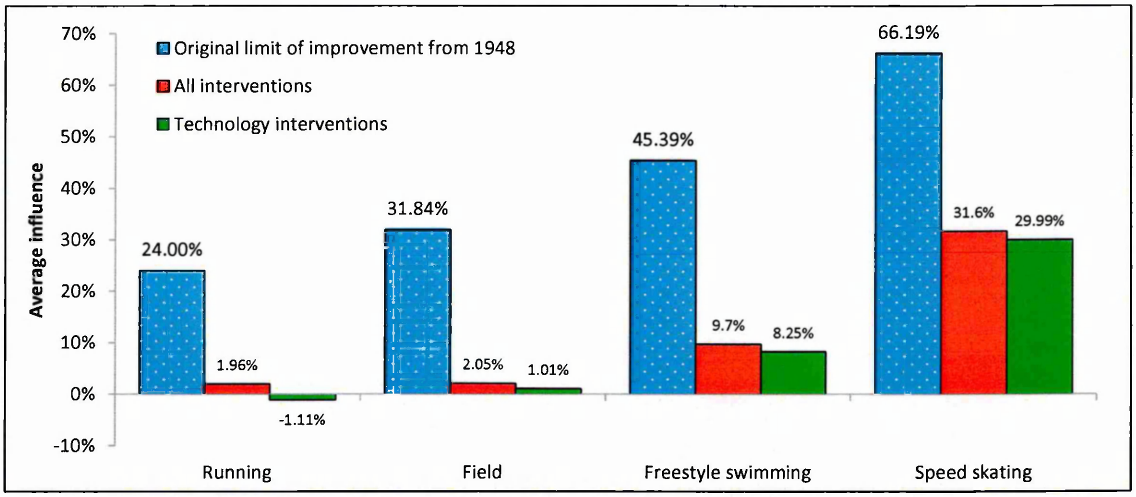


Figure 10.3: Average size of all interventions in the different sports categories which are still believed to influence performance

The specific effect of the different interventions in terms of percentage performance improvement and raw figures are shown in tabular form from Table 10.2 to Table 10.9.

Table 10.2: Usain Bolt named effect in the 100 metres men's event shown in terms of performance improvement and raw performance figures

Sport	Event	Usain Bolt effect (% increase)	Usain Bolt effect (s)
Track	100 m (men)	0.7%	-0.03

Table 10.3: Population influx effect in the middle and long distance men's running events shown in performance improvement and raw performance figures

Sport	Event	Population influx effect (% increase)	Population influx effect (s)
Track	800 m (men)	4.0%	-2.19
	1500 m (men)	4.3%	-4.94
	5000 m (men)	6.2%	-26.54
	10000 m (men)	5.6%	-51.29
	42195 m (men)	12.0%	-542.58

Table 10.4: Fully automatic timing effect shown in terms of performance improvement and raw performance figures

Sport	Event	FAT effect (% increase)	FAT effect (s)
Track	100 m	-3.8%	0.20
	200 m	-2.7%	0.29
	400 m	-2.3%	0.54
	100 m (women)	-3.0%	0.18
	200 m (women)	-0.4%	0.05
Freestyle swimming	100 m (men)	-1.5%	0.42
	100 m (women)	-3.8%	1.28

Table 10.5: Fosbury Flop effect in the high jump event shown in terms of performance improvement and raw performance figures

Event	Fosbury flop effect (% increase)	Fosbury flop effect (m)
High jump(Women)	3.7%	0.06

Table 10.6: Composite poles effect in the men's pole vault event shown in terms of performance improvement and raw performance figures

Event	Composite poles effect (% increase)	Composite poles effect (m)
Pole Vault (men)	11.1%	0.47

Table 10.7: The effect of changes in the javelin design shown in terms of performance improvement and raw performance figures

	Rule change COM 1986/1999		Tail roughness 1991		Hollow uptake 1953 -1956	
Event	(% increase)	(m)	(% increase)	(m)	(% increase)	(m)
Javelin (men)	-12.2%	-8.39	0.0%	0.00	7.5%	5.13
Javelin (women)	-2.2%	-0.99	-3.9%	-1.70	3.9%	1.70

Table 10.8: The effect of different swimming technologies shown in terms of performance improvement and raw performance figures

		Linear uptake 1970-1976		Swim suit 2000		Swim suit 2008		Swim suit 2009	
Gender	Event	(% increase)	(s)	(% increase)	(s)	(% increase)	(s)	(% increase)	(s)
Men	100 m (men)	4.5%	-1.28	1.7%	-0.47	3.6%	-1.02	5.2%	-1.47
	200 m (men)	2.4%	-1.52	2.7%	-1.38	1.6%	-1.04	4.6%	-2.94
	400 m (men)	4.8%	-6.55	2.8%	-0.47	1.0%	-1.32	2.7%	-3.73
	1500 m (men)	9.9%	-54.67	1.7%	-7.59	1.8%	-10.28	2.0%	-11.41
Women	100 m (women)	11.5%	-3.70	3.0%	-1.00	2.4%	-0.77	5.2%	-1.69
	400 m (women)	7.9%	-12.17	1.9%	-2.90	2.7%	-4.14	4.8%	-7.39

Table 10.9: The effect of different speed skating technologies shown in terms of performance improvement and raw performance figures

		Artificial ice		Skin suits		Clap skates	
Gender	Event	(% increase)	(s)	(% increase)	(s)	(% increase)	(s)
Men	500 m (men)	2.0%	-0.44	0.8%	-0.17	9.9%	-2.12
	1000 m (men)	19.7%	-9.07	6.0%	-2.83	16.5%	-7.66
	1500 m (men)	6.8%	-4.76	3.9%	-2.76	16.2%	-10.99
	3000 m (men)	16.4%	-24.08	2.8%	-4.25	19.6%	-28.59
	5000 m (men)	11.7%	-29.26	3.9%	-9.95	11.9%	-29.80
	10000 m (men)	5.4%	-28.75	2.8%	-15.02	12.5%	-65.07
Women	500 m (women)	11.7%	-2.95	n/a	n/a	18.7%	-4.64
	1000 m (women)	11.7%	-6.21	n/a	n/a	26.8%	-13.81
	1500 m (women)	n/a	n/a	4.5%	-3.80	30.1%	-24.04
	3000 m (women)	n/a	n/a	2.9%	-5.24	24.5%	-41.81

10.2.(a) Summary: Running

Running is the sport with the lowest modelled technology influence, with an average influence from technology of -1.11 %. The only technology modelled in running was the introduction of fully automatic timing or FAT. The introduction of these new timing systems in running had the apparent effect of reducing performances by eliminating the delay in starting hand-held stop watches, and errors in pre-judging finishes of races due to human reaction time.

The largest intervention effect seen in running events was the influx of an additional population modelled in the middle and long distance running events. This intervention was not technology-based but had a significant influence on performance, with a maximum modelled effect in the men's marathon event with a positive increase of 11.5 % in performance.

It is not surprising that being a simplistic event, running is currently influenced very little by any technological advancement which has been accounted for in this study. The only technology found to apparently influence running performance is fully automatic timing with a negative effect on measured performance values.

10.2.(b) Summary: Field events

Field events include a variety of different sports which fall into two main categories, which are jumping and throwing events. In broad terms field events are no more influenced by technological interventions than running; however there are some exceptions to this.

The long jump, shot put and the discus are events in both the jumping and throwing categories, which were modelled without any technological interventions. Out of all the athletic events examined, the men's long jump event has been modelled to increase the least from 1948, reaching a predicted limit of performance improvement at 11.03 %.

This is similar to the maximum predicted performance improvement in the men's 100 m at 13.68 %, and could indicate that performance in these two events is related. Foster (2010) highlights that the physical requirements in both the long jump and the 100 m events are similar and improvements in both these events appear to follow the same trend.

The women's shot put, discus and javelin events are predicted to improve maximally out of all the field events examined, with the natural improvement from 1948 envisaged to plateau at 52.61 %, 57.17 % and 54.25 % respectively. It is believed that the striking improvements seen in these events are due to the baseline performance figures in 1948, and that women's throwing events were behind with respect to levels of competiveness and the size of competing population. This means that the baseline performance figures in women's throwing events are lower than the comparable men's events.

The high jump and the pole vault jumping events were influence by technological interventions. These are the uptake of the Fosbury Flop technique (women's only), which was modelled from 1968 to 1972, as well as the introduction of composite poles in 1956, which was modelled with a linear uptake from 1956 up until 1972 (Table 10.5 and Table 10.6). Within this current study the Fosbury Flop in the high jump appeared to have a relatively minor influence on performances, with a modelled influence of 3.69 % in the women's event. In contrast the composite poles in the men's pole vault were found to have a significant influence on performance with a possible 12.36 % increase in performances. The technique change in the high jump has previously been perceived to have greatly influenced performances, but shown here there was no effect found in the men's event and only a minor influence of 3.69% in the women's event. Composite poles in the pole vault event have also been found to greatly influence performance. Haake (2009) estimated that the pole vault world record in 1996 would be 5.24 m. In this study it is expected that the performance height of the pole vault world record without composite poles would be slightly higher at 5.57 m.

The javelin event is the field event which is most effected by technology changes. A negative influence from a change in rules which moved the centre of mass forward by 40 mm in the men's event is believed to have caused a drop in performance of 12.19%. This is nearly four times greater than the modelled centre of mass change in the women's event at 3.68 %. However this rule change in the women's event contains high error bounds, meaning an effect from this rule change is difficult to quantify in the women's event. The other rule change which outlawed tail roughness changes, which reduced the drag of the javelin, has been found to have no measureable influence on javelin performance. The uptake of hollow javelins from 1953 to 1956 has been shown to have a positive on javelin performances, resulting in 7.46% and 6.51% improvements in performance for the men's and women's events respectively.

10.2.(c) Summary: Freestyle swimming

Freestyle swimming performance improvement follows a similar trend to both field events and running. Modelled maximum improvements from 1948 in freestyle swimming from the global improvement is higher when compared to running events, with improvements ranging from 38.76% to 55.46%. These values are comparable to some of the women's field events, and could indicate that competitive levels in freestyle swimming are also low when compared to some other athletic events like the 100 m sprint, which has seen less of an improvement. On average the predicted improvement from all freestyle swimming events examined is 45.39%, and is on average greater than both running and field events. The sport of swimming is believed to be less natural than the previous two athletic disciplines and could be another reason for the greater global development of the sport due to the optimisation of various swimming techniques.

Swimming suit technology developments in 2000, 2008 and 2009 have appeared to increase performance, with an average influence of 2.30, 2.16 and 4.08% respectively. These interventions have now been excluded following a rule change in 2010. The uptake of technology from 1970 to 1976 had an average measured influence of 6.83%, which is greater than any of the recent suit developments. It appears that as the development of swimming performance in the freestyle was at an earlier stage, the introduction of technologies in the 1970s was eclipsed by the global improvement. The global improvement function has a steeper gradient which means year-on-year natural developments would have made it harder to witness any improvements from technology developments. Even though the technology developments in the 1970s may have had a greater influence on performance than the recent suit changes, there was no rules to govern the uptake of these new technologies.

The modelled influence of swimming suits in 2008 and 2009 preceding the rule change banning the majority of improvement in swimming suit design from 2000 is shown in Figure 10.4.

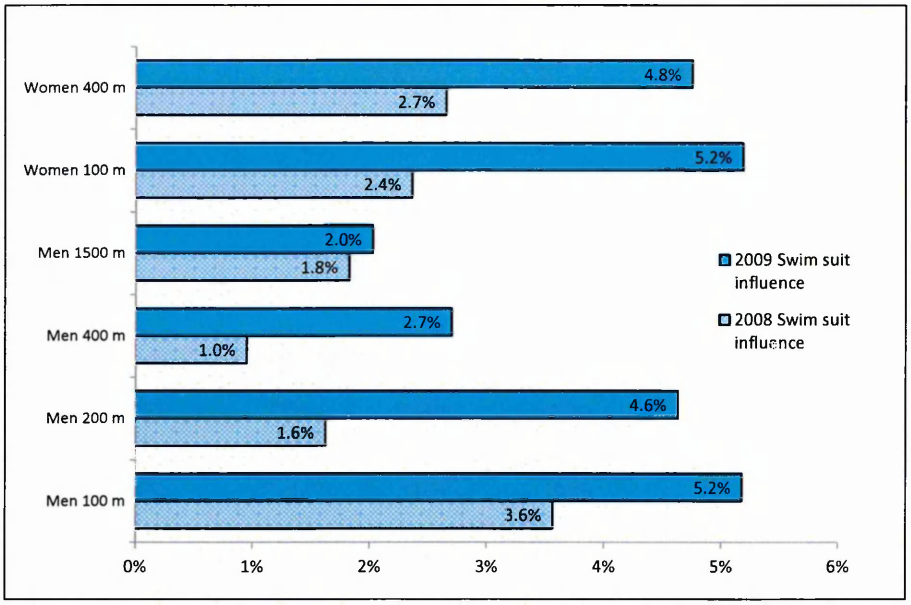


Figure 10.4: The influence of the different swimming suit technology introduction in 2008 and 2009, which were both banned in 2010.

The step changes used to account for swimming suit changes in 2008 and 2009 have shown that there is a maximum effect of a 3.57% improvement with the 2008 intervention, and a 5.19% for the 2009 intervention. The modelled effect in 2009 is on average greater than in 2008, and it is believed that suits introduced in 2009 were more beneficial to performance than the suits introduced in 2008. The Olympic function may have also reduced the measured magnitude of the 2008 intervention, as 2008 was an Olympic year and performance was expected to be slightly elevated due to the four year cycle. The combination of the increased Olympic performance, in addition to benefits gained from the suits, are likely to have influenced the large number of world records seen in 2008. The un-modelled World Championship effect, along with the 2009 suit changes, is likely to be the cause of the increased performance which saw the achievement of more world records this year. Full body swimming suits are no longer exerting any effect on current swimming performance due to the rule change in 2010. This was a good example of a technology being allowed to develop but then being abruptly discontinued, resulting in a unique opportunity to gauge its influence on performance.

10.2.(d) Summary Speed skating

Speed skating is the final sport examined and appears to be subject to the greatest influence on performance from technology, with an average improvement of 29.99%. Development of performance from 1948 is also the highest in this sport with an average predicted limit of performance across all events examined at 66.19%. The reasons for this will be discussed in detail shortly.

Artificial ice development has been modelled in some speed skating events, and has been showed to have a possible maximum influence of 19.72%. The influence of artificial ice is believed to influence the higher speed and longer distance speed skating events due to the increased efficiency of the gliding stokes. The 500 m event appears to be the event least affected by this, and this could be due to the dominance of the acceleration phase, and the necessity for more pushing strokes in this event.

Skin suits have been modelled with a step change in 1976. All speed skating events were modelled for a skin suit effect with an average influence across all events of 3.31%. The measured influence from skin suits is small with high confidence bounds, and so it is difficult to confidently discern any effect at all. Clap skates are the final technology introduced into the speed skating events. There is a large measured influence, modelled through a linear uptake from 1996 to 2002. The introduction of clap skates has been responsible for greatest technological influence measured in this study, with an average influence of 18.27% across all events.

10.3 Universal interventions

Some interventions are believed to influence the majority of sports, and have been labelled as universal interventions. These will now be summarised.

10.3.(a) Olympic Games

The modelled influence of the Olympic Games is now shown for all events where an effect could be measured in Table 10.10.

Table 10.10: The effect of the Olympic Games in all events where an effect was found, shown in terms of performance improvement and raw performance figures

Sport	Event	Olympic effect (% increase)	±	Olympic effect (Raw, seconds or metres)	±
Track	100 m (men)	0.33%	0.24%	0.02	0.01
	200 m (men)	0.44%	0.22%	0.05	0.02
	400 m (men)	0.43%	0.23%	0.10	0.05
	800 m (men)	0.16%	0.22%	0.09	0.12
	1500 m (men)	n/a	n/a	n/a	n/a
	5000 m (men)	n/a	n/a	n/a	n/a
	10000 m (men)	0.36%	0.35%	3.28	3.25
	42195 m (men)	n/a	n/a	n/a	n/a
	100 m (women)	0.71%	0.31%	0.04	0.02
	200 m (women)	0.66%	0.35%	0.08	0.04
	800 m (women)	0.49%	0.65%	0.35	0.46
Field	Long jump (men)	0.31%	0.18%	0.02	0.01
	High jump (men)	0.17%	0.14%	0.00	0.00
	Pole vault (men)	0.34%	0.36%	0.01	0.02
	Shot put (men)	0.45%	0.54%	0.07	0.09
	Discus (men)	0.48%	0.47%	0.24	0.24
	Javelin (men)	0.20%	0.31%	0.14	0.21
	Long jump (women)	0.38%	0.29%	0.02	0.02
	High jump (women)	0.37%	0.21%	0.01	0.00
	Shot put (women)	0.86%	1.00%	0.11	0.13
	Discus (women)	0.97%	0.60%	0.41	0.25
	Javelin (women)	0.52%	0.54%	0.23	0.24
Freestyle swimming	FS 100 m (men)	0.76%	0.42%	0.22	0.12
	FS 200 m (men)	0.69%	0.64%	0.44	0.41
	FS 400 m (men)	0.53%	0.71%	0.74	0.99
	FS 1500 m (men)	0.90%	0.84%	5.10	4.74
	FS 100 m (women)	0.93%	0.77%	0.31	0.25
	FS 400 m (women)	0.86%	0.80%	1.35	1.26
Speed skating	SS 500 m (men)	0.95%	0.56%	20.02	0.12
	SS 1000 m (men)	1.31%	0.82%	21.02	0.58
	SS 1500 m (men)	n/a	n/a	n/a	n/a
	SS 3000 m (men)	n/a	n/a	n/a	n/a
	SS 5000 m (men)	1.03%	0.81%	21.02	2.08
	SS 10000 m (men)	1.39%	0.76%	22.02	4.06
	SS 500 m (women)	0.71%	0.98%	23.02	0.25
	SS 1000 m (women)	1.47%	1.42%	24.02	0.77
	SS 1500 m (women)	0.70%	1.73%	25.02	1.48
	SS 3000 m (women)	0.99%	1.36%	26.02	2.43

It is apparent that the majority of interventions that have significantly influence sporting performance are from technology introductions, however there are two interventions which are not technology related; these are the influx of an addition competition population modelled in men's middle and long distance running events and the Olympic Games.

Throughout the athletic evolution from 1948 up until 2010 the Olympic Games appears to have had a small influence on performance figures within athletic events. This influence is small in comparison to other interventions such as technology and the influence of an additional competing population. The error bounds on the Olympic parameter were also high which could indicate that there is no Olympic effect in some events at all. The Olympic Games effect is the smallest intervention measured and so the least influential factor modelled in this study. However in the future, as human athletic performance reaches a theoretical limit, an Olympic Games or championship effect may become more prominent. The rationale for this is that as global development begins to stagnate, as is predicted to occur in all sports before the end of the 21st century, performances may begin to vary only from season to season.

10.3.(b) Drugs

The magnitude of drug interventions modelled with a step change is shown in Figure 10.5 below.

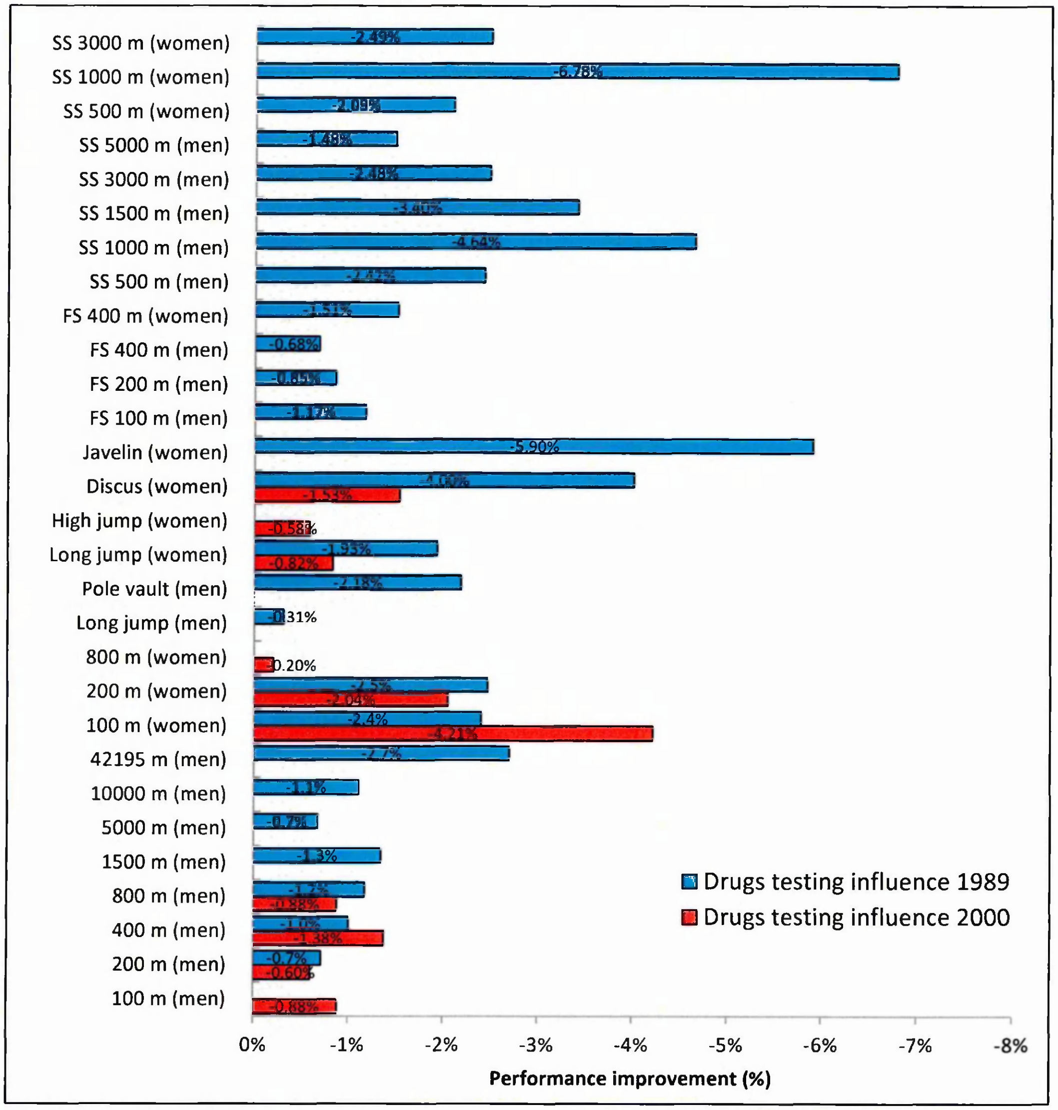


Figure 10.5: The size of the drug testing intervention (1989 and 2000) in events where an effect was modelled

10.3.b.(i) Summary drug testing procedures 1989

The influence of improved out-of-season drug testing procedures in 1989 was modelled in the majority of events examined. A step change was used to model this intervention, in conjunction with a linear uptake model of drugs where appropriate. The step change intervention only accounts for the introduction of better drug testing and not the uptake of illegal drug use. Therefore this modelling function only measures the drop in performance due to the better drug testing procedures. The maximum effect was witnessed in the 1000 m women's long course speed skating event at -6.78% with the smallest influence in the men's long jump at -0.31%. This drug testing step change was witnessed in the majority of sports examined. This indicates that drug testing procedures introduced after 1988 were successful at reducing the effect of illegal drugs on performances.

10.3.b.(ii) Summary drug testing procedures 2000

The step change used to model the drug testing procedural changes in 2000 and the formation of WADA was only apparent in a few events, and suggests that this intervention is not as universal as the 1989 procedural change. The effect was found in running and field events, with a maximal effect in the women's 100 m at -4.21% Figure 10.6.now shows the measured peak influence of performance-enhancing drugs modelled through a linear uptake and decline function.

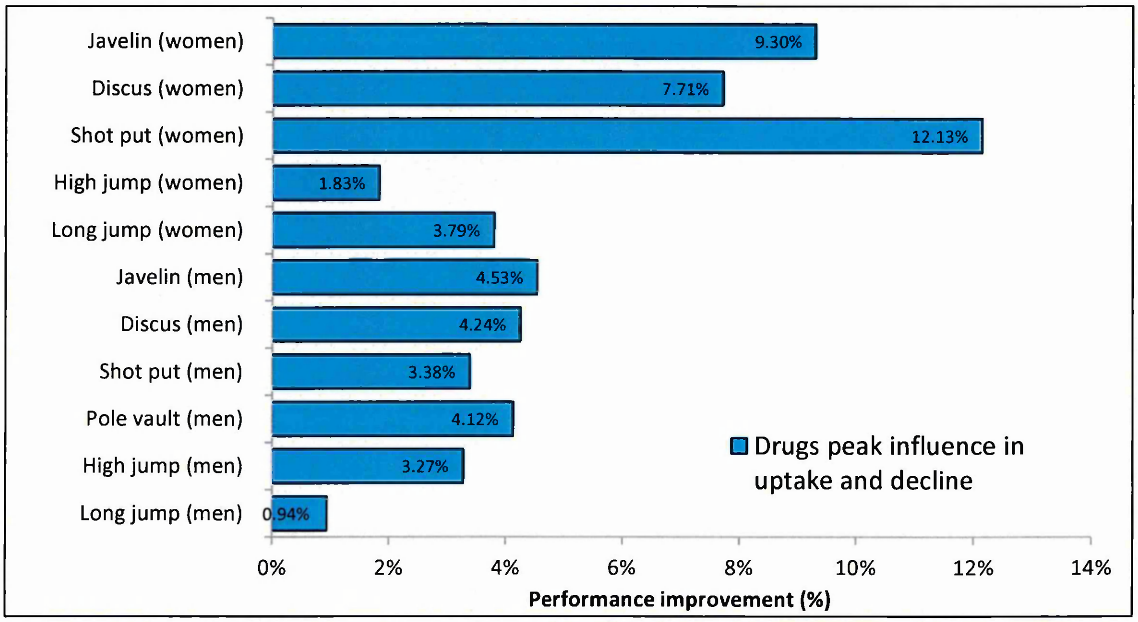


Figure 10.6: The peak size of the drug influence where an uptake and decline model was used

10.3.b.(iii) Summary uptake and decline model

The linear uptake and decline function was used to model the uptake of illegal drug use and then subsequent reduction in drug use through better drug testing procedures. A decline function was found to best represent the residual performance-enhancing effects in only the men's and women's field events. The maximum effect of drug use using this function was found in the women's shot put, with a measured influence of 12.13%.

As this function was only found to be appropriate in field events, this suggests that drug testing procedures in 1989 did not have as a dramatic or instantaneous an influence as found with the other events examined. There are two potential reasons for this; these relate to characteristics of performance-enhancing drugs used in different sports, as well as the age of elite athletes. In general, the performance-enhancing drugs favoured by field event athletes exert their physiological effects over a greater length of time when compared to drugs used by running, swimming and speed skating athletes. This effect is also compounded by the greater age of field event athletes, who are on average older than counterpart athletes. If field athletes competed before and after a drugs intervention, theoretically they could still benefit from the improved performance gained by illegal drug use, even after the drug-use has been discontinued.

Due to the step changes and linear decline witnessed in athletic performances, it is believed that performance-enhancing drugs are not a substantial contributor to current levels of athletic performance. Due to the secretive nature of illegal drug-use it is difficult to precisely quantify the magnitude of their influence. However, from this study there is plentiful evidence to suggest that in the late 1980s, performance-enhancing drugs had a significant effect on performance, especially in field events.

10.3.(c) Global improvement

From 1948, the original expected maximum global improvement in all running events examined was an average of 24.0 % (Figure 10.3). This is similar to the expected global improvement in the field events, and indicates that on average running and field events will improve a similar amount from 1948 without external interventions. In contrast on average the natural evolution from 1948 for freestyle swimming performance is predicted to improve by 45.39%, and speed skating by 66.19 %. These values are significantly higher than the predicted evolution of running and field events. One key reason for this is thought to be related to the competitiveness levels of each sporting discipline in 1948. Track and field events were hugely popular, with a large global competing population, and this meant that there were comparatively high levels of competition and development in those sports. In comparison the less developed sports such as swimming and speed skating had a smaller competing population, resulting in lower levels of competitiveness and therefore development. Logically this leads to greater improvements in events with lower competitive levels in 1948, as events approach and reach the theoretical performance limit, due to the increased potential for improvement. Another reason for greater advancement in the freestyle swimming and speed skating events may relate to their less intuitive nature. As these events are less innate to humans in evolutionary terms, optimal swimming or skating techniques may yet be achieved. This stands in contrast to running and field events, where throwing, running and jumping techniques can be seen as being more natural to humans, and may therefore be closer to being optimised.

Show in Figure 10.7 is the global improvement trend of athletic performance from the start of modern athletic competitions as described by Nevill (2005). The trend follows the shape of a 's' shaped sigmoidal model. In the early stages of modern sport development (section i) from the late 1800 onwards, where sporting performance developed slowly as modern sport was taken up and spread throughout the world, any technological intervention influenced the levels of performance significantly. Intervention (1) shows that a large increase in performance over the general or global improvement trend. In section (ii) of the trend athletic performance increases rapidly as globalisation and the spread of sport increases performance. Technological interventions of similar magnitudes to the previous section have a lower impact on measured sporting performance, as the global improvements are large, obscuring the technological advantages.

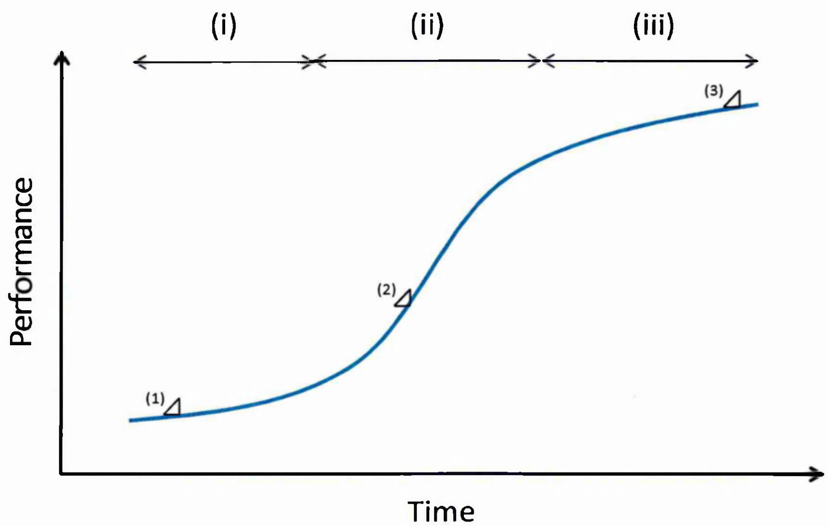


Figure 10.7: Typical athletic performance improvement trend from the start of modern sporting competition in the mid to late 1800s.

The latest phase (section iii) of the global athletic performance trend shows a reduction in rate of improvement. Again the same level of technological intervention in this phase has a more visible influence on levels of performance. This means that any early technological introductions may have had a significant effect on performance, but this effect is difficult to separate from the overall global performance trends. The question is raised of whether the recent technological advances, such as the introduction of full body polyurethane swimming suits, should be banned based upon their influence on performance alone. Interestingly it has been shown that the level of technological interventions in the 1970s are likely to have had a greater influence on freestyle swimming performance than the recent developments in swimming suits, and these early technologies were not banned.

10.4 Final conclusion

In conclusion there have been many influencing factors which have improved human athletic performance. From 1948 the main driving force behind improvements in athletic performance is believed to be the increase in the size of competition population, which is seen in all athletic events. This overall improvement in athletic performance has been gauged through an exponential improvement function. Technology has influenced the natural progression of athletic performance in both a positive and negative way. For the purposes of the final conclusion, technologies believed to have influenced sporting performance have been divided into two three distinct categories. These are physical technologies such as sporting equipment or hardware, new techniques such as the Fosbury Flop, and finally facilities such as artificial ice rinks. Shown in Figure 10.8 is a Venn diagram which shows all factors which have contributed to improvements seen in human athletic performance. Finally the Olympic Games have also been shown to influence performance. The overall influence of the Olympic Games is minor in terms of performance improvement, but as athletic performance levels plateau an Olympic periodic effect on performance may become more prominent.

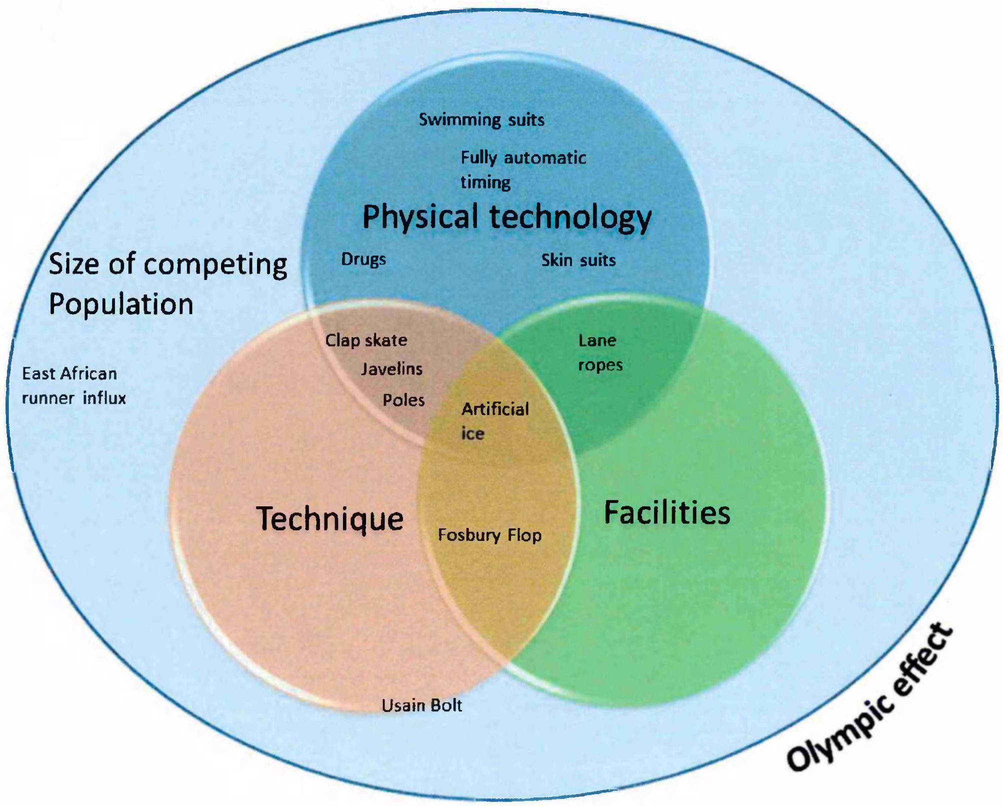


Figure 10.8: Venn diagram of interventions believed to currently influence athletic performance shown with different categories of sports technology and technologies examined in this study placed in appropriate locations

Technology has been found to influence different sports by varying degrees. The nature of the sport appears to dictate the level of influence from technology. In running and some specific field events like the long jump, shot put and discus, technological interventions play a minor role on performance levels. These sports can be seen to be the purest and most intuitive, and are predominantly based on an athlete's physiological ability. The high jump also appears to be relatively un-influenced by the effect of technology. The introduction of the Fosbury Flop would appear to exert only a minimal effect. However its true impact may well be masked by the nature of the event, with the emphasis being on beating opponents by only a small margin, rather than on jumping as high as possible.

Technology has been shown to influence the pole vaulting and the javelin events significantly. The composite pole technology and hollow javelins have been found to improve performance, with rule changes in the javelin decreasing performance significantly. Technology also influences long course freestyle swimming events and long course speed skating. The clap skate has been found to significantly influence performance in skating, along with technology such as goggles, hats and full-body shaving in swimming.

Performance-enhancing drugs and full-body swimming suits are technologies which increased performance before their influence was removed from current performance levels. The actual level of illegal drug influence may never be fully quantifiable due to the secretive nature of its use.

Initially it was theorised that technology played a major role in sporting development, but this research has shown that the levels by which technology influences sport are significantly lower than changes seen due to natural sporting evolution. This implies that technological interventions play a relatively minor role in sporting development currently. However as athletic performance plateaus, as is predicted to occur in the near future, the effect of technology should become more prominent. In these circumstances, technology may be the only factor improving human athletic performance. This means that in order to keep sports fair, the regulation of technology in sport will become more relevant than ever before.

10.5 Limitations and future work

10.5.(a) Variations in maximum PII from 1948

All sports appear to have developed by varying degrees from the baseline start year of 1948; this is primarily believed to be because of the variation in competitive levels different sports. One way of dealing with this in the future is to reverse the performance improvement index calculations. This means taking the base line year as the most recent year performance data can be collected. For this study the comparison year would be 2010. As performance levels are believed to be reaching a plateau, taking a baseline figure at the most recent year would mean levels of competitiveness across all sport would be at a similar level. Additionally, all interventions can be related to this absolute limit, instead of a baseline year in the past.

10.5.(b) What would the top 25 list tell us?

The top twenty five lists used in this study as a single yearly performance measure could also be examined further. The range of the top 25 or similar statistic could be used as a measure of competitiveness. The levels of competiveness in different sports could then also be examined on a yearly basis. Following on from this global human performance trends could be examined in more detail, data sets could be expanded before 1948 and different models such as a sigmoidal functions used to model the data more accurately and to account for the detrimental effects of the world wars. Quantification of the global improvement, i.e. the rate of change of performance trends, can also be further examined and the justification for using a simple exponential function explored.

10.5.(c) The use of human energetic models

Finally the use of human energetic models could be used to more accurately quantify the energy expenditure levels in completing various athletic tasks. This will give a more accurate indication of the levels of energy expenditure over and above the existing performance improvement index.

10.5.(d) Independent data points

For any experiment where multiple measurements over time are recorded and regression analysis used to test a hypotheses it is assumed that these individual measurements are independent. In this study it has been assumed that the mean of the top 25 performance lists are independent data. However, if examining sporting performance figures over a number of years, one individual prolific athlete will influence yearly performance figures over a period. This will then create an era where performance data is dependent on that athlete who enters the top performance lists over many years. One way to make performance data truly independent is to take only single performances from each individual athlete i.e. just use their top performance figure. However, this will drastically reduce the size of the data set and the re-compiling top 25 lists so that no single athlete appears more than once in any list will be difficult. A reduction in the size of the top performance list could be plausible with a mean of the top 5 single athletes with their personal best that year. Further work needs to be carried out to consider methods of procedure to make human performance data a truly independent data source.

10.5.(e) Limitations of the PII

Throughout this thesis the performance improvement index or PII has been assumed to be an accurate way of quantifying and comparing sporting performance, but this may not be the case. It was found that a general increase in frontal may have meant the index under estimates performance improvements in the 100 metres, but changes in frontal area of marathon runners would not influence sporting performance significantly. The result of this may mean that the performance improvement limit in the 100 metres men's event is underestimated. However, as the modelling techniques used in this study explored the differences in index values, not considering frontal area is believed not to influence the size of gauged interventions. Further work is required to examine the true nature and significance of accounting for frontal area changes within the performance improvement index and the general accuracy of the performance improvement index as a whole. As mentioned earlier the use of human energetic models could be a means of carrying this out.

10.5.(f) The exponential model

For this study it was decided to use a three parameter exponential modelling function to describe the underlying global trend. The main limitation to this is that the exponential model assumes that the highest rate of change in performance improvements occurs at the start of the period being examined, in this study 1948. This however may not be true for all events. The justification for using a three parameter model is explained in detail in chapter four. In brief, it was found that this shape of function for running events fitted the current performance data set from 1948 the best, with the greatest R^2 adjusted coefficient. The use of a sigmoidal function which contains an extra parameter was therefore found not to be beneficial to the fit of global models. This sigmoidal function was therefore excluded from this study. Additionally it is believed that from 1948 onwards sporting performance would follow an exponential function. This would suggest that the greatest acceleration of performances would be found at the start of the period where general human improvement is easiest. A plateau would then be seen as human improvement becomes more difficult, and a limit is approached. An increase in the rate of change in performance improvement would only occur due to an external intervention such as technology introduction or population influx. These additional interventions would be then modelled with additional functions.

The assumption that all sporting events have a maximum acceleration at the start of the period being examined could be inaccurate. The use of sigmoidal functions as used by Nevill (2005) will avoid this assumption, and could easily be integrated in to the methods developed in this thesis to quantify interventions. All that is required is a change to the global improvement function, with a subsequent reassessment of results. The exponential function would be replaced by a four parameter sigmoidal function, and an additional parameter programmed into the graphical user interface. The disadvantage with using a sigmoidal function with the techniques developed in this study is that this model may inadvertently account for a technological intervention. This means that when additional modelling functions are applied over the top of the global function, the effect of interventions may be missed and not modelled. This phenomenon may have already occurred in a recent study (Balmer et al. 2012) where the effect of the introduction of new pole vaults could not be accounted for.

To explore whether the underlying assumptions and exponential models chosen in this study are appropriate to model the overall athletic improvement, the modelling error or residuals can be examined. The residual value is the difference between a modelled and an observed data point. Positive residual values indicate that for that particular data point the model overestimates observed data. For negative residual values the model underestimates observed data.

If an appropriate model is chosen the residuals should be normally distributed with a mean value of zero. Additionally, residuals should be independently distributed over time and not show any serial correlation. This is where successive residuals in a time sequence have a tendency to be similar in certain regions. For the case of an exponential model, if there was an increase in the rate of change of performance improvement at any point there would be an area of successive positive residuals followed by a region of successive negative residuals. If this is found to be the case, the exponential function and/or the original assumptions may be inappropriate to model this performance data.

The residuals from the final models were calculated for a selection of different sports. Shown below in figures 10.9 and 10.10 are the residual values for the final models in different events modelled in this study. As expected, residual values are both positive and negative, with the mean approximately zero.

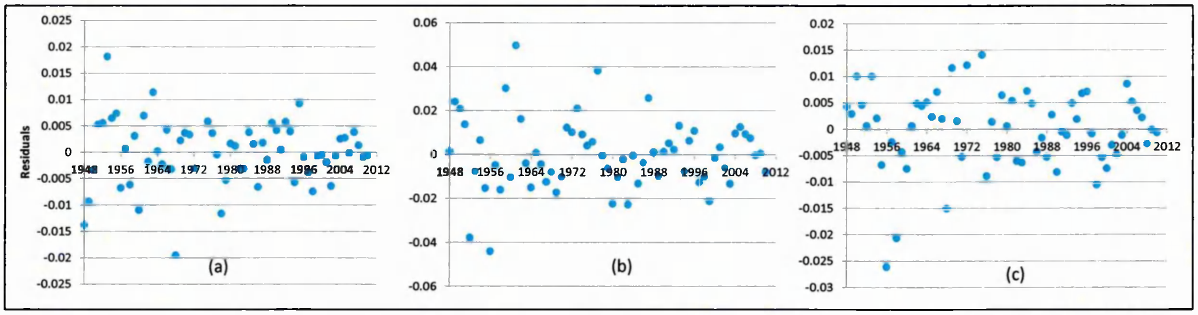


Figure 10.9: Residual values plotted against year for the final models for the (a) men's 100 m (b) men's marathon and (c) women's 100 m.

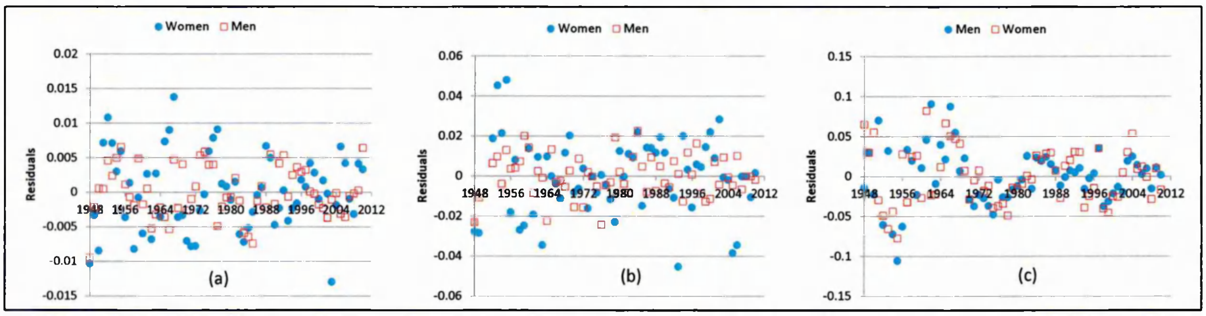


Figure 10.10: Residual values plotted against year for the final models for the (a) High jump (b) 100 m long course freestyle swimming event and (c) 1000 m long course speed skating event.

By considering only the residuals against time plots show in figures 10.9 and 10.10 it is difficult to gain any meaningful information. Firstly, to explore the normality of the residuals, a normal probability plot can be produced (Chambers et al 1983). Residuals have been plotted against their cumulative probability for each of the final models already examined and shown in figures 10.11 and 10.12.

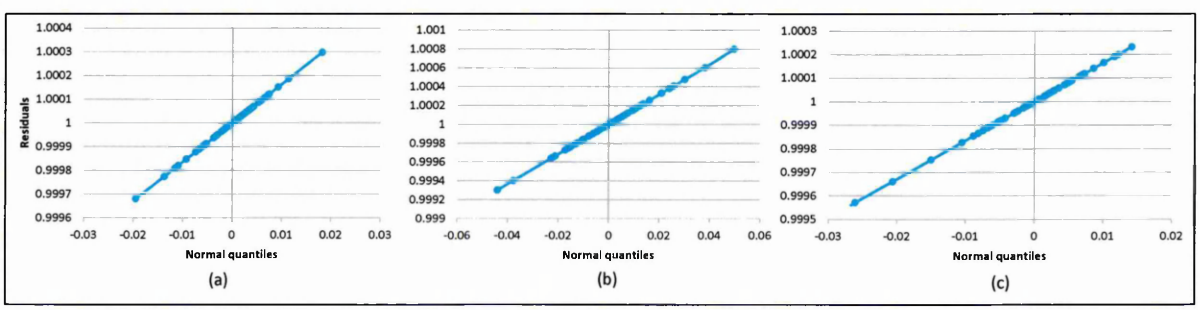


Figure 10.11: Residual values plotted against normal quantile for the final models for the (a) men's 100 m (b) men's marathon and (c) women's 100 m.

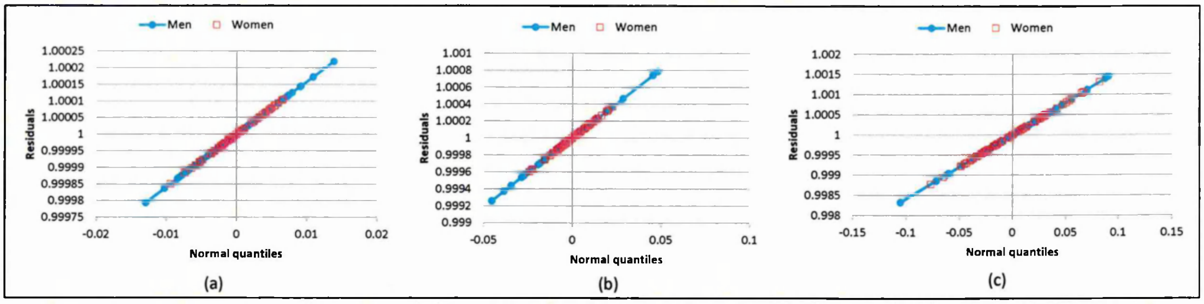


Figure 10.12: Residual values plotted against normal quantile for the final models for the (a) High jump (b) 100 m long course freestyle swimming event and (c) 1000 m long course speed skating event.

It is apparent that all plots in figures 10.11 and 10.12 show straight lines. This indicates that all the residuals are normally distributed about the mean zero. This means that the current exponential functions satisfy the modelling assumption, which is that the residuals are normally distributed. If this were not the case, there could be some underlying structure in the residuals which would signify an inappropriately selected model.

A popular test to examine whether the residuals are independent over time and not serial correlated is the “Durbin-Watson test” (Durbin and Watson 1950). An alternative to the Durbin-Watson test is the “runs test” (Draper and Smith 1988). As the runs test ignores the sizes of the residuals and only uses their signs in a time sequence, it is easier and faster to apply.

A runs test can be used to checks a randomness of a sequence of two values. In this case it can be used as a simple method to establish whether the pattern of positive and negative residuals is “unusual”, which could indicate a poorly selected model. In a runs test, the number of "runs” or *r* is the number of times two variables switches in a sequence. In the case of a residuals time sequence, this is therefore the number of times they switch from positive to negative. A check can be made to see whether the number of runs in a sequence is extreme or not. If the number of runs is an extreme case, or very unlikely to occur, this will indicate serial correlation. This will indicate that an inappropriate model has been selected. In a small sequence the probability of obtaining each different configuration of runs can be calculated. This is not practical for longer sequences however. For longer sequences and higher runs, as seen with the residuals examined here, a normal approximation is used for a discrete distribution of r where the mean,

$$\mu = \frac{2n_1n_2}{n_1+n_2} + 1 \tag{48}$$

and variance

$$\sigma^2 = \frac{2n_1n_2(2n_1n_2 - n_1 - n_2)}{(n_1+n_2)^2(n_1+n_2 - 1)} \tag{49}$$

where n_1 and n_2 is the number of plus and negative signs respectively. If $r < \mu$ then a lower-tail test is used where the standard score,

$$z = \frac{(r - \mu + 0.5)}{\sigma} \tag{50}$$

If $r > \mu$ an upper -tail test is used where the standard score,

$$z = \frac{(r - \mu - 0.5)}{\sigma} \tag{51}$$

Upon finding the standard score values the probability of obtaining this value or smaller is looked up from standard normal tables. The results of applying the runs test to the residuals of the models examined here are shown in table 10.11.

Table 10.11: Result from the runs test when applied to the residuals of the selection of final models.

	100 m men	Marathon men	100 m women	High jump men	High jump women	100 m Freestyle men	100 m Freestyle women	1000 m Speed skating men	1000 m Speed skating women
Total runs:	31	23	19	23	25	34	29	23	23
Negative:	31	30	33	28	30	30	31	32	31
Positive:	30	33	32	35	33	31	30	31	32
μ:	31.4918	32.4286	33.4923	32.1111	32.4286	31.4918	31.4918	32.4921	32.4921
σ^2:	14.9876	15.4246	15.9884	15.1095	15.4246	14.9876	14.9876	15.4880	15.4880
Test:	Upper tail	Upper tail	Upper tail	Upper tail	Upper tail	Lower tail	Upper tail	Upper tail	Upper tail
z:	-0.2562	-2.5280	-3.7494	-2.4726	-2.0188	0.7770	-0.7728	-2.5390	-2.5390
P:	0.3974	0.0057	0.0001	0.0068	0.0217	0.7823	0.2206	0.0055	0.0055

Unusually low numbers of runs occur in 6 out of the 9 models examined (highlighted in red). This means that in these cases the arrangements of signs of the residuals is not random, which could mean the exponential model is not appropriate and cannot model certain aspects of the improvement trend. Therefore the sigmoidal model may be more appropriate in these cases.

If the original assumption is true and human performance from 1948 does follow an exponential decay trend (with maximum acceleration in 1948), the results from the runs test may indicate that some interventions have not been accounted for. For example if there is an increase in the rate of improvement of human athletic performance after 1948, which is attributed to an unknown intervention which was not accounted for, unusual serial correlated residuals will occur. This does not mean that underlying exponential model is not appropriate, rather that the method in searching and accounting for every intervention is difficult. Therefore for the purposes and assumptions made in this study it is believed that the exponential model is justified. However, the appropriateness of using sigmoidal models on these data sets, as well as expanded datasets (pre 1948), will be carried out in future work.

10.5.(g) Pre-determined periods

One major downside to the methods described to quantify sporting interventions in this thesis is the prerequisite of determining the start and end date of an interventions influence. The selection of these dates is based upon historic evidence. Without this initial historic evidence an intervention cannot be modelled. Therefore this method cannot detect unknown interventions, but only model interventions which are actively searched. Therefore the methods are somewhat subjective to the dates selected for a modelling function to be applied. Linear functions may correctly model the peak influence of an intervention if dates are selected correctly. However, the true magnitude of an intervention's influence is based upon the dates selected. To alleviate the subjective nature of this methodology the use of an additional sigmoidal function as used by Balmer et al. (2012) could be employed which objectively models the increase in rate of change of performance which is indicative of an intervention.

10.5.(h) Population remains constant

The true nature of the influence of population size on athletic performance remains a mystery. If a competing population size remains constant, would there be an increase in performance? This is a difficult question to answer as the size of a competing population is very hard to gauge, how could the number of people in the world competing in the 100 m be quantified. There are many people who compete in the 100 m sprint throughout the world, but what fraction of world's population has the access to compete in athletic sports? It is therefore very difficult to exactly quantify the size of the competing population. However, further analysis of the influence of population may involve the examination of performance improvements of a pre-determined athletic population such as an individual nation and the national records of that country.

10.5.(i) Data mining and machine learning approach

It is believed that in the future the searching for and gauging of an intervention's influence upon athletic performance will be completely automated and objectively carried out using data mining techniques. The methods developed within this study are a good starting point to develop the computer algorithms required. Techniques developed could one day enable the autonomous tailoring of training programs to maximise an athlete's performance and also search for illegal intervention such as the use of performance enhancing drugs.

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